Impact of dietary shifts in India on greenhouse gas emissions, land use, water use, and food expenditure: a nationally-representative study

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Abstract

Background

Food production is a major driver of environmental change, while dietary risks are the leading cause of global disease burden. Studies suggest that adoption of healthy diets in high-income countries can provide environmental co-benefits. However, little is known about such options in low and middle-income countries. India is home to one-fifth of the global population, and experiencing complex nutritional challenges, alongside critical environmental pressures on its ability to produce food. This project assesses the potential for dietary change to improve health and diet-related environmental footprints in India.

Methods and results

A systematic review assessed the sustainable dietary patterns studied in the literature, and their impacts on a range of environmental indicators, to understand which diets may lead to improved environmental and health outcomes. Adoption of sustainable diets is generally estimated to reduce environmental footprints, though large variations in reductions are seen across sustainable diet types. Following national dietary guidelines may be a relevant public health goal with both environmental and health benefits. A comparison was undertaken of a number of dietary intake data sources in India, examining relative differences in overall intake, and intake of key food groups, to better understand data suitability for sustainable diet analyses. The comparison highlighted the 2011-2012 National Sample Survey (NSS) household expenditure surveys as a relevant data source for the project, though data sources showed high variability in intake, particularly for a set of key nutrient-dense food groups. The NSS and environmental footprint data were matched to estimate the change in greenhouse gas (GHG) emissions, land use (LU), and water footprints (WFs) that may result from national adoption of healthy dietary guidelines, and contrasted this with a scenario of widespread uptake of “affluent” diets. A shift to healthy guidelines in India would result in a small increase in environmental footprints (4-5% for GHG emissions, LU and WFs), though this national result masked large variations among sub-samples; for example, healthy diet shifts among those who consume above recommended dietary energy could decrease emissions by 6-16% across the three environmental indicators. Shifts to affluent diets would result in large increases of about 19-36% across indicators. Lastly, differences in cost were assessed between observed healthy and lower-footprint diets, and average diets with sufficient dietary energy (“adequate” diets). Overall, healthy diets with lower footprints were slightly more expensive than an adequate diet. Large variations were observed among sub-samples of the population: improved diets were particularly more expensive for lower-income individuals and rural residents, while cheaper, or had no difference in price, for individuals in the highest quartile of socioeconomic status, and for urban residents. Higher expenditure on improved diets was particularly associated with fruit and vegetables, and dairy.

Conclusions

Achieving the critical public health goal of healthy diets while minimising diet-related environmental footprints in India may require three broad strategies: increasing the efficiency of agricultural production, alongside efforts to improve the affordability of healthy dietary change, and the active promotion of healthy and lower-footprint diets for those who can currently afford them.

Declaration

I, Lukasz Aleksandrowicz, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

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Additional publications

The following is a list of additional publications that have resulted from work on the thesis:

Alae-Carew C, Bird FA, Green R, Choudhury S, Harris F, **Aleksandrowicz L**, Milner J, Joy EJM, Agrawal S, Dangour AD. Future diets in India: a systematic review of food consumption projection studies. 2019 *Global Food Security* (*Under revision*)

Green RF, Joy EJM, Harris F, Agrawal S, **Aleksandrowicz L**, Hillier J, Macdiarmid JI, Milner J, Vetter SH, Smith P, Haines A, Dangour ADD. Greenhouse gas emissions and water footprints of typical dietary patterns in India. 2018 *Science of the Total Environment* 643:1411-1418

Joy EJM, Green R, Agrawal S, **Aleksandrowicz L**, Bowen L, Kinra S, Macdiarmid JI, Haines A, Dangour ADD. Dietary patterns and non-communicable disease risk in Indian adults: secondary analysis of Indian Migration Study data. 2017 *Public Health Nutrition* 20:1963-1972

Aleksandrowicz L, Green R, Joy EJM, Vetter S, Harris F, Story M, Haines A. Environmental effects of shifting to healthy diets in India: a nationally representative study. 2017 *Lancet* 389:S1 [Conference abstract]

Milner J, Joy EJM, Green R, Harris F, **Aleksandrowicz L**, Agrawal S, Smith P, Haines A, Dangour ADD. Projected health effects of realistic dietary changes to address freshwater constraints in India: a modelling study. 2017 *Lancet Planetary Health* 1:e26-e32

Picchioni F, Aurino E, **Aleksandrowicz L**, Bruce M, Chesterman S, Dominguez-Salas P, Gersten Z, Kalamatianou S, Turner C, Yates J. Roads to interdisciplinarity: working at the nexus among food systems, nutrition and health. 2017 *Food Security* 9:181-189 [Conference report]

Aleksandrowicz L, Green R, Joy EJM, Smith P, Haines A, Harris-Lovett S. How do our food choices affect the environment? 2017 *Environmental Science Journal for Teens* [Adaptation of PLoS systematic review for a younger audience]

Vetter SH, Sapkota TB, Hillier J, Stirling CM, Macdiarmid JI, **Aleksandrowicz L**, Green R, Joy EJM, Dangour ADD, Smith P. Greenhouse gas emissions from agricultural food production to supply Indian diets: implications for climate change mitigation. 2017 *Agriculture Ecosystems & Environment* 237:234-241

Aleksandrowicz L. How do sustainable diets fit into the climate agenda? 2016 *Public Health Reviews* 37: 23 [Commentary]

Picchioni F, **Aleksandrowicz L**, Bruce MM, Cuevas S, Dominguez-Salas P, Jia L, Tak M. Agri-health research: what have we learned and where do we go next? 2015 *Food Security* 8:291-298 [Conference report]

Aleksandrowicz L, Haines A, Green R. Sustainable diet studies show co-benefits for greenhouse gas emissions and public health. 2015 *Advances in Nutrition* 6:282-283 [Letter to the editor]

Preface

This thesis is written in a research paper style format. The first chapter is a general introduction to the importance of diets in the context of global environmental change and health, and explains the project aims and structure. The second chapter is a review of methodology used in the sustainable diets literature. Chapters three to six are research papers, and chapter 7 is an overall discussion of the thesis. The first three papers have been published in peer-reviewed journals, while the fourth paper is in preparation for submission. Supplementary materials for research papers are included immediately following the reference list within each paper. All papers are presented as unformatted word-processed manuscripts to maintain a consistent style throughout the thesis, and for ease of reading and annotation. Alternatively, if the journal format of the published papers is preferred, these are available through open access (citations below), and are the same version as those presented in this PhD:

Aleksandrowicz L, Green R, Joy EJM, Smith P, Haines A. The impacts of dietary change on greenhouse gas emissions, land use, water use, and health: a systematic review. *PLoS One* 2016; **11**(11): e0165797

Aleksandrowicz L, Tak M, Green R, Kinra S, Haines A. Comparison of food consumption in Indian adults between national and sub-national dietary data sources. *British Journal of Nutrition* 2017; **117**(7): 1013-1019

Aleksandrowicz L, Green R, Joy EJM, et al. Environmental impacts of dietary shifts in India: a modelling study using nationally-representative data. *Environment International* 2019; **126**: 207-215

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List of abbreviations

CO_2eq	Carbon dioxide equivalent
FAO	Food and Agricultural Organization
FBS	Food balance sheets
FFQ	Food frequency questionnaire
GHG	Greenhouse gas
HCES	Household consumption and expenditure survey
HIC	High-income country
IHDS	India Human Development Survey
IMS	Indian Migration Study
LCA	Life Cycle Analysis
LMIC	Low- and middle-income country
LU	Land use
LUC	Land-use change
MPCE	Monthly per capita expenditure
NCD	Non-communicable disease
NIN	National Institute of Nutrition
NSS	National Sample Survey
WHO	World Health Organization
WF	Water footprint
WFN	Water footprint network

1. Introduction

1.1 Global environmental change and health

Major improvements in human health and well-being over the last century have come at the cost of widespread degradation of natural ecosystems[1]. These systems provide crucial services that underpin the health of humanity, and their continued destruction threatens to roll back the health improvements made to date. Key environmental pressures, among others, are greenhouse gas (GHG) emissions, water use, and land use.

Climate change, driven by anthropogenic greenhouse gas (GHG) emissions, poses considerable risks to human and natural systems through its various effects on environmental and biophysical systems [2]. Direct pathways impacting health include heat stress, flooding, and extreme weather, while indirect pathways are mediated through changes in vector borne transmission, impacts on crop yields and micronutrient content, air pollution as well as socially mediated effects such as migration and possibly conflict[3]. Health impacts are expected to be seen across most major disease burden categories; infectious disease, non-communicable disease, and injuries. Globally, impacts of climate change on health are already being felt, and are expected to increase into the 21st century without drastic actions to mitigate further emissions[4,5].

About half of all available freshwater is consumed for human use, with more than 60% of rivers globally now dammed[6,7]. Maintaining sufficient freshwater for human use is vital for providing safe drinking water and sanitation, and freshwater is additionally a critical input for food production systems[8]. Misuse of water by industrial processes globally also leads to chemical contamination. It is estimated that by the middle of the century, almost 4 billion people will be living in areas facing severe water stress[6].

Globally, human activity has modified a substantial amount of the earth's surface, with estimates ranging from at least 25% to over 50%[6,9], largely driven by urbanisation and agriculture. These changes in land use produce a loss of biodiversity and soil[10], both of which are critical for agricultural systems and nutrition. Loss of soil additionally increases the risks of flooding, and biodiversity loss reduces the availability of nutritious food sources, novel compounds for medicine and other uses, and disrupts a number of underlying ecosystem services that help purify air and water[11]. Additionally, methods of land clearing such as burning create air pollution, and further increase GHG emissions[1].

1.2 Contributions of agriculture and diets to global environmental change

Agricultural production is a major contributor to the global environmental changes outlined above. While advances in agricultural production since the middle of the twentieth century have dramatically increased food availability, reliability, and affordability in many regions of the world[12], this success has been a major driver of environmental degradation. For example, agriculture is estimated to contribute about 20-25% of all global GHG emissions[13]. Within this, livestock production is responsible for the majority of agricultural emissions, the largest share of which comes from digestion (enteric fermentation) in ruminant animals, and feed production for livestock[14]. Across agricultural supply chains, the primary stage of production (including agricultural inputs such as pesticides and feed for livestock) contributes the largest share of GHG emissions from the food system, ranging from 50-90%[14-16]. Emissions during production can vary widely by location and method of food production; for example, emissions from producing a given crop across various farms can differ by a factor of 50[17]. Land-use change, which is largely caused by the clearing of land for agricultural uses, and the associated loss of carbon from soils and vegetation, also contributes a substantial portion of emissions - though with wide variability depending on the estimation method – and these emissions are mainly produced during deforestation for cropland and pastures[13,15].

Much of the total land mass appropriated by humans is due in part to agriculture; it is estimated that croplands and pastures occupy about a third of ice-free land globally[18]. The rate of land-use change from agriculture is increasing rapidly in some regions, such as low- and middle-income countries (LMICs), due to a rising demand from both local and global consumers for animal-based foods, other food crops such as palm oil, as well as crops for non-food uses such as biofuels[1].

Water is a critical input into food production, and globally, agriculture accounts for about 70% of water withdrawals through irrigation[19]. In many regions, this contributes to aquifer depletion, and agriculture is also a large driver of water pollution, from fertiliser and pesticide run-off, and livestock effluent[20]. Measurements of water footprints (WFs) are composed of three parts: blue WFs are the ground and surface water used for production via irrigation; green WFs are the amount of rainfall used for production; and grey WFs are the amount of water required to dilute agricultural pollution to levels meeting water quality standards[21].

The impacts of water use are not always felt in the regions where food is consumed, as “virtual water flows” through food trade can see the withdrawal of water in a location with adequate water availability or efficient growing conditions, while consumption of the product occurs elsewhere[22].

The environmental impacts described above are the most commonly studied of agriculture and diets, though agriculture affects a variety of other indicators. The planetary boundaries framework has set out a “safe operating space” for humanity, in the form of thresholds for nine earth system indicators, the breaching of which would entail serious destabilization of natural environmental systems[23]; these include land and water use, and climate change, as described above, and agriculture contributes significantly to other thresholds, including phosphorus and nitrogen use and biodiversity loss. Others impacts of agriculture include desertification, ecotoxicity, and natural resource depletion[23,24].

Across the environmental indicators of GHG emissions, WFs, and land use (LU), the broad food groupings contributing most to agricultural footprints, from highest to lowest, are similar; ruminant meat, poultry and pork, dairy, and plant-based foods, respectively, with some exceptions within groupings – such as nuts and pulses having, in some cases, higher water impacts than some animal-based products[17,25,26]. This trend broadly applies regardless of the functional unit used, such as environmental impact per kg of food, per calorie, or per gram of protein[26-30]. As the demand for food quantity and diversity grows, fuelled by population growth and economic development, the pressures on these environmental domains are expected to increase, which in turn, may place additional challenges on agricultural production, and contribute to health risks through the health and environmental change pathways described above.

1.3 Diets, health and nutrition

While production of food creates substantial environmental pressures, food consumption patterns and associated nutritional risks are also major determinants of human health. Poor diets are now the leading risk factor for the global burden of disease[31].

Of 141 countries for which data exist, 124 experience more than one form of the "triple burden" of malnutrition: broadly, consuming too few calories, consuming too many, and consuming insufficient nutrients[32]. At a global level, prevalence of anaemia among women is 33%, overweight among adults is 39%, while 22% of children under 5 years of age are stunted[32].

Population-level dietary changes are often driven by changes in urbanisation, demography, income, and global trade, with consequences for nutrition-related burdens of disease. Historical stages of nutrition and physical activity have been categorised into 5 broad dietary patterns: hunter-gatherers, monoculture and famine, industrialization and receding famine, nutritional-related non-communicable disease (NCD), and healthy diets/desired behavioural change. The movement by societies between these patterns is known as the nutrition transition[33]. High-income countries

(HICs) sit within the nutrition-related NCD stage, while the transition between receding famine to increasing levels of NCDs is prominent in many LMICs; though different populations within a country may be experiencing drastically different nutritional situations, such as the case in LMICs which simultaneously experience high prevalence of both undernutrition and overweight and obesity[32]. To date, widespread adoption of the last stage of healthy diets and physical activity has not yet occurred in any country[34].

The diet-related risks factors for NCDs are those of excess dietary energy and/or individual components such as salt, sugar, and saturated or trans-fats, and low intake of nutrient-dense foods such as nuts, fruit, and vegetables (alongside behavioural risk factors such as physical activity and others). In many cases, urbanisation and growing incomes are the main drivers influencing the affordability and accessibility of energy-dense and refined foods, at the expense of dietary diversity and nutrient-rich foods[35,36].

1.4 Role of dietary shifts in mitigating environmental change and improving health

Given the role of food production and diets as important drivers of both health and environmental change, the interactions between nutrition and environmental footprints have been increasingly explored to find solutions for both global challenges. In particular, a rapidly growing body of literature is investigating the opportunity of whether healthy diets can also deliver environmental benefits. Such diets are commonly referred to as “sustainable diets” in the literature, and loosely draw on a definition provided by the Food and Agriculture Organization (FAO): "Sustainable Diets are those diets with low environmental impacts which contribute to food and nutrition security and to healthy life for present and future generations. Sustainable diets are protective and respectful of biodiversity and ecosystems, culturally acceptable, accessible, economically fair and affordable; nutritionally adequate, safe and healthy; while optimizing natural and human resources"[37] (Figure 1). According to this definition, sustainable diets should encompass considerations in four broad domains: health, environment, affordability (for consumers and producers), as well as other social and cultural aspects. Much of the literature to date focuses on the extent to which a dietary shift (often, but not always, implied to be healthy to varying degrees) can mitigate environmental footprints, and less frequently measures the direct health impacts of such shifts or their affordability. Other socio-cultural considerations highlighted in the FAO definition, such as traditional knowledge of food, culinary traditions, fair labour practices, and food preparation education, are rarely assessed[38,39]. An additional gap in the literature is studies focusing on LMICs, where the context of nutritional and environmental challenges is often different than for HICs*.

* Given the emphasis in the literature on environmental outcomes of dietary change, studies typically refer to sustainable diets as ones which are environmentally beneficial, and in most cases, healthy. While this interpretation is not as comprehensive as the FAO definition, for consistency and conciseness, the wording in the thesis sections will do the same, unless otherwise specified.

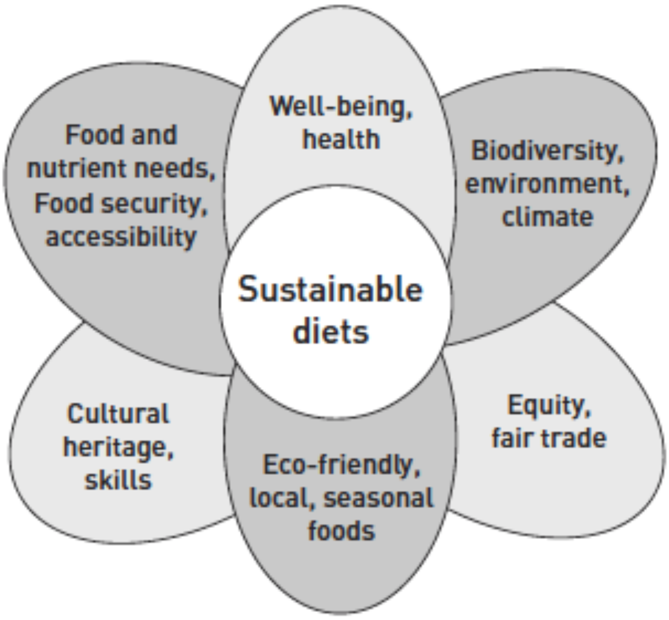

Figure 1: Schematic representation of the components of a sustainable diet according to the FAO definition. Source: FAO 2012[37].

Mitigation strategies to reduce environmental footprints from diets and agriculture are classified as either supply- or demand-side measures. Supply-side measures focus on technological improvements to reduce the amount of footprints per unit of food produced; for example, the Food and Agriculture Organization (FAO) estimates that 30% of the livestock sector's emissions could be reduced if all global producers adopted the same practices as the most efficient livestock producers, including in feeding practices and manure management[14]. Demand-side measures refer to consumer dietary change, aiming for adoption of healthier and environmentally-sustainable diets[26,40-43]. Consumer change can be supported through measures such as promotional campaigns and advertising, product labelling, community education, retail store design, and pricing strategies[44].

Few studies have estimated the relative importance of supply- and demand-side measures in mitigating environmental change, and the results are mixed depending on the region, assumption on future trajectories, and the environmental indicator assessed. Global assessments have pointed to both technological improvement in agriculture as the area with relatively higher potential for GHG mitigation[45,46], while others to food-demand management[47], while a study in the EU concluded that demand- and supply-side measures have about equal opportunities[48], and an analysis of land use showed that dietary choice is a stronger mediator than yield efficiency improvements[49]. Nevertheless, the evidence has highlighted that neither approach on its own is a silver bullet; rather, both approaches are necessary to ensure that healthy and diverse diets can be delivered for a growing population, while staying within environmental planetary boundaries.

In relation to demand-side approaches focused on consumer dietary choice, much of the literature has been devoted to investigating the extent to which dietary changes can reduce GHG emissions, and less so on WFs and LU impacts. A very small number of studies assess other indicators such as biodiversity loss[25]. The main drivers of reduced environmental footprints within dietary choice are largely the substitution of high-footprint with lower-footprints food (such as replacing red meat with plant-based foods), and reducing overall dietary intake, as most diets in HICs have an excess of calories[25,41,50,51]. A major consideration of demand-side approaches, however, is the difficulty of their implementation. Effective reductions in environmental footprints would require wide-scale changes in consumer behaviour, and as described above, healthy diets currently have low prevalence in populations, with no countries yet achieving widespread adoption of healthy eating patterns.

Some of the difficulties inherent in dietary change and promotion of healthy and low-footprint diets may be due to the complexity of defining sustainability, across indicators, regions, and for specific populations. For example, public awareness around sustainable eating often includes principles of purchasing food that is locally produced and in-season. These factors, however, may not always lead to lower dietary footprints, due to transport's modest contribution to GHG emissions relative to other food system stages, and the relative environmental efficiencies of producing crops in certain geographical regions[52-54]. For example, tomatoes grown in Spain for UK consumption emit fewer GHG emissions than their UK-produced equivalents which are grown in greenhouses, even with the additional transport distance required[15]. Similarly, organic food, sometimes considered an environmentally-beneficial option, can have higher or lower footprints compared to conventionally-grown food, depending on the indicator and food type assessed[55]. There are also a number of trade-offs inherent between environmental sustainability and health, as sugar production has among the least environmental impacts per kg or calorie of product[26,27], palm oil has lower water and land use than oils with healthier fat profiles[17], and guidelines for higher fish intake may be difficult to realise in the face of the fragile state of many global fisheries[56,57].

1.5 Cost of healthy and environmentally sustainable diets

Affordability is one of the primary drivers of dietary choice, and may pose a barrier to improving diets in cases where healthy and sustainable diets are more expensive than current average diets[58]. Lack of affordability of healthy diets is implicated in all forms of malnutrition. For example, where individuals face poverty, a sufficient level of dietary energy may be unaffordable – or in cases where energy-dense foods may be more affordable than nutrient-rich foods, the resulting dietary patterns may lead to overweight and obesity, and/or micronutrient deficiencies.

Empirical evidence generally shows that healthy dietary patterns are more expensive than less healthy ones[59,60]. Energy-dense foods that are high in fat, sugars, or starches, or are nutrient-poor, are priced relatively lower than nutrient-rich foods such as fruit, lean meats, vegetables, pulses, and unrefined grains[59,61-63]. However, some studies have found the opposite effect, in that healthy diets can be cheaper than unhealthy ones, and in these cases the effect seems to be mediated by healthy diets having fewer calories (and therefore requiring less food expenditure)[64,65], or the existence of subsidies for healthy foods[66]. Additionally, prices of healthy foods have been rising faster than those of processed foods in recent decades[60,63,67]. The difference in price between nutrient-dense and nutrient-poor foods may be explained by a history of food systems driving efficiencies in processed food production, as well as agricultural subsidies for staple grains[39,68].

Households in LMICs, on average, spend between 40-70% of their incomes on food[69,70] (and poor households in HICs may also face similar challenges), and therefore there is little flexibility to increase food expenditures to adopt healthy diets. Global food price elasticities (the change in demand for a food item in response to a change in price) show that, when food prices increase, food demand drops most in lower-income versus higher-income countries, with similar relative trends between low- and high-income households within countries. Additionally, the demand for nutrient-rich foods, like fruits and vegetables, fish and dairy drops more than for cereals and oils[71].

The effect of these patterns is that low-income individuals are at greater risk of not being able to afford healthy diets, and face higher nutrition-related health risks than wealthier individuals. For example, the higher cost of healthy food seems to explain the socioeconomic disparities in consumption of healthy diets[72], and in turn, food prices may explain most of the differential in obesity rates between low- and high-income individuals[73].

The literature on the costs of diets that include both health and environmental sustainability considerations is more recent, and less extensive than that focusing on the costs of healthy dietary choices alone - and so far offers a mixed picture. Studies using mathematical optimisation to construct hypothetical diets have shown that it is possible to model a healthy and sustainable diet that is either cheaper or cost-neutral, compared to average diets[74-77], while those using observed diets or non-optimisation approaches show mixed results, with healthier and more sustainable diets being more expensive[78-82], and less expensive[83-86]. Sustainable diets share many of the same features as healthy diets (such as a high proportion of fruit and vegetables in the diet, and deriving proteins from a mix of plant- and animal-based sources), and therefore it is not surprising that many studies would find healthy and sustainable diets to also be more expensive than average, relatively unhealthy intake patterns. However, sustainable diets additionally have some features, such as an emphasis on eliminating or drastically reducing animal-sourced foods in favour of plant-based foods, that may have a unique impact on costs, in relation to diets that only focus on health considerations. Only one published study to date seems to have compared the costs of healthy and sustainable versus healthy diets, finding that healthier and more sustainable diets were less expensive than solely a healthy diet, mainly due to a lower overall amount of dietary energy intake in the former[83].

The costs of healthy and sustainable diets may face additional pressures in the future, as climate change is anticipated to decrease the nutritional content and yield of crops[87-89], as well as reduce agricultural labour productivity[90], which may increase the price of food, and lead to negative implications for poverty and health in many regions[91,92]. This likelihood makes the importance of identifying nutritionally-adequate, environmentally sustainable, and low-cost dietary options paramount.

1.6 Where this project fits in

A growing body of literature has modelled the environmental impacts of population shifts to sustainable diets[26,42,93-95]. The diversity of approaches across these studies is large; using a range of environmental impacts (GHG emissions, LU and WFs, among others), across different countries with differing baseline diets, proposing a wide spectrum of alternate healthy and sustainable diet types, and using different assumptions and data. Not all studies have aimed to maintain realistic or culturally acceptable intake patterns in the sustainable diets proposed. The vast majority of the literature is based on studies in HICs, where health, environmental impacts, and dietary patterns may interact in different ways than in LMICs. For example, with relatively higher undernutrition rates, dietary patterns in LMICs may benefit from an overall increase in the amount of dietary energy consumed, or increased intake of animal source foods, which provide a source of high-quality protein and micronutrients. Additionally, few studies have assessed the cost of the proposed dietary shifts. Although large-scale changes in consumer behaviour are challenging to implement, food cost is an important predictor of dietary choice, and therefore understanding affordability is critical to the potential success of dietary interventions.

This project focuses on the environmental impacts of adopting healthy diets, and their affordability, in India – a country with one-fifth of the world's population, high rates of both undernutrition and overweight/obesity, a diversity of dietary patterns, as well as substantial environmental pressures on its food production.

1.7 Setting of project: background on Indian diets, agricultural production, and food access

Dietary patterns in India

While encompassing enormous cultural, geographical and dietary diversity, average Indian diets are typically plant-based, consisting largely (in terms of absolute quantities) of cereals, followed by fruits and vegetables, and dairy, with varying amount of other food groups such as meats, pulses, oils, and sugar[96]. Spices also feature prominently in Indian diets, particularly when compared to Western cuisine.

These food groups combine in varying extents to produce a number of dietary patterns across the country. Several studies have attempted to categorise and define typical Indian dietary patterns, though have used different analytical methods and geographical scales, and are therefore difficult to compare[97-99]. On average, southern India tends to have the highest dietary diversity in terms of number of different food groups eaten per day (largely due to higher overall socioeconomic status), and higher diversity is also seen among urban vs. rural households, and higher- vs. lower-income households[97].

Cereals feature prominently in Indian diets, and particularly for rural populations who rely heavily on them due to lack of access or affordability of other food groups. Rice is the dominant cereal in India, though there is variety across regions; diets in southern and eastern India tend to be rice-based, while those in the north and west are wheat-based[97,98]. Intake of other cereals, such as millet, barley, and sorghum, is lower than rice and wheat, and has been decreasing over the last several decades[74].

Fruit and vegetable intake is often low and below recommended guidelines; poor households may have difficulty accessing or being able to afford these, while in other households, other items such as cereals, dairy, and processed foods may displace fruit and vegetable intake. Indian cuisine features a large diversity of fruits and vegetables, though much of the national intake is weighted towards several common types. For fruit, these are bananas, mangos, coconuts, apples and oranges[100]. Potatoes, if compared alongside other vegetables (and while technically a tuber, they are partially classified as vegetables by the Indian dietary guidelines[101]), are the most commonly consumed vegetable, followed by onions, tomatoes, green leafy vegetables, cauliflower, and gourds[100].

South India typically has the highest fruit intake, while North and East India tend to have higher than average vegetable intake[97,102]. Individuals in urban areas consume higher amounts of fruits and vegetables than rural areas, and intake for high-income households is much higher than in lower-income households[100].

Dairy is popular in all parts of India, and after cereals, is the major source of protein in diets[102,103]. Dairy features throughout Indian dishes; as a firm cheese (paneer), as milk and yogurt, and is used to produce ghee, used as a cooling oil. Milk and ghee also features prominently in many Indian desserts. While widespread nationally, dairy intake is much higher for wealthier households, in northern states than in the south of the country, and slightly higher in urban areas[97,98].

Meat intake on average is low, though while India is sometimes thought to be a largely vegetarian country, the number of self-identified and practicing vegetarians is less than 30%[104]. Meat intake is occasional, with about 6% of the population consuming it daily (compared to 45% for dairy)[103], and is typically used as an accompaniment in meals, such as in stewed curries or biryani (a largely rice-based dish), rather than as a main feature[103,104]. The most common types of meat, in order of highest to lowest quantity of intake, are fish, poultry, beef and lamb, and pork[103].

Low intake is due to a number of accessibility and affordability, as well as cultural and religious, reasons. Meat is highly perishable, and food systems in India are often locally based, with an under-developed cold chain transport and storage network[104,105]. Many religions in India have varying degrees of restrictions on meat – for example, Jains eat none, Muslims do not eat pork, and Hindus and Buddhists vary in their meat intake, which is influenced by their region and/or socioeconomic status[106]. However, meat intake in India is now increasingly linked to positive socioeconomic connotations of being progressive, modern, and secular[104].

Pulses are the third highest contributing food group to protein intake in India, behind cereals and dairy. Consumption of pulses is higher than that of meat (about 30 g/capita/day, compared to 8), and at this level, is also double that of Western countries[107], though far lower than that of dairy intake in India (about 175g/capita/d)[97]. Red gram (known as pigeon pea in other countries) is the most commonly consumed pulse, double that of other varieties (green gram, lentils, black gram, and chickpeas) which have about equal average consumption per capita among them. Intake is higher in urban than rural areas, with consumption also generally higher among richer households[108]. Regionally, the highest-consuming states are scattered across all major regions (south, central, west, and north), though the mountainous north-east states have the lowest pulse consumption (and conversely, the highest meat intake)[108,109].

The last two to three decades have seen shifts in the intakes described above. These shifts have largely been defined by sizeable decreases in cereals and increases in intake of dairy and oil; smaller decreases in vegetables, and increases in meat and eggs; and largely no change in pulses and fruit[97].

Agricultural production

Agriculture employs over half of India's workforce, and is the most important sector of the Indian economy[110,111]. India is a major global producer of food, and ranks as the first or second largest producer of rice, wheat, pulses, fruits and vegetables, and livestock, among others[111]. The substantial scale of agriculture in the country is aided by a large amount of arable land, a diversity of climatic conditions that can accommodate a variety of crops, and a generally temperate climate that allow for more than one cropping season per year[111].

More than 80% of farms in India are on small or marginal tracts of land (less than one hectare)[112], and the average size of farms continues to decrease as sections of holdings are passed down within families, or leased out for farming activity. This has consequences for farming productivity, as small and irregularly shaped land is less amenable to the use of machinery, irrigation, and various public goods, and farmers cannot take advantage of bulk pricing for inputs such as fertiliser and seeds[110]. Levels of mechanisation are low, at about 50%, compared to 90% in developed countries[113]. Agricultural households also remain removed from agricultural extension services, which deliver skills, knowledge and best practices to improve farming practices and livelihoods, with almost 60% of farming households receiving no such assistance[114].

Agricultural employment is split fairly evenly between the genders, with men making up 53% of labour (though comprising two-thirds of those who control and cultivate land)[115], and the number of women in agriculture has been growing as males move to urban areas for work. Socially disadvantages groups such as Scheduled Tribes and Castes tend to have smaller farms[112]. Most farmers own their own land, with only 10% of land under cultivation being rented out or sub-contracted from other land owners, though this varies widely across Indian states[114]. Farming households often do a mix of jobs, with those on marginal land plots often providing labour for larger farms, and on average, about 10% of a farming households' income comes from non-farm work[114]. Despite the number of income streams, more than half of all agricultural households are in debt, particularly those on smaller tracts of land[114].

While India is a major exporter of agricultural products, the majority of food consumed in the country is produced domestically[116]. Much of production and consumption is further linked at more local levels, largely as storage, cold chain transport, and distribution systems that would facilitate widespread trade across the country are relatively under-developed, and much of the crops grown are used by farming households for their own consumption[117]. Most states dictate that farmers sell their products at state-owned procurement markets (known as mandis), though this system features many intermediary actors, which tends to squeeze out farmers' profits. While the Indian government is attempting to loosen and update this legislation, the majority of agricultural output is still instead sold to private traders[112,117]. This leaves farmers liable to variable demand and prices, though contract farming is an emerging approach, in which an agreement on the quantity, quality and price of goods is established between a producer and a private trader[112].

Food access

Much of the food purchased in India is through traditional retail settings like locally-owned neighbourhood shops, roadside vendors, and street markets. These outlets, known as the "unorganised sector", comprises over 95% of market share in the country, compared to the "organised sector" of modern retail such as supermarkets and hypermarkets[118,119]. Particularly prevalent in the unorganised sector are "kiranas", or individual, family-owned shops, estimated to number 12 million nationally. These have maintained high popularity due to their proximity to many residents, which allows many individuals who cannot buy in bulk to make frequent trips, their procurement of locally-relevant items, and because the local nature of shops permits regular customers to purchase items on credit[120]. Kinaras largely sell staples such as rice, pulses, oils and snacks[120], while fruits and vegetables are mainly purchased from smaller street vendors, and wholesale produce markets[121].

However, the organised sector is growing quickly, after having emerged around 2005[118,122], and while most modern retail chains are domestically-owned, an increasing number of international chains are also appearing[122]. The emergence of modern retail has coincided with increasing urbanisation, levels of education, standards of living, and global trade, and its average customer is therefore more likely to be an urban dweller and wealthier, relative to the unorganised sector. However, these outlets are not exclusively restricted to urban and higher-income areas, as retail chains in India, in contrast to their development in Western countries, have had relatively early penetration of small cities, lower-income populations, and in some cases, rural areas[122].

It is not yet clear to what extent this trend is influencing the type of food purchases in India, as the organised sector holds a small fraction of the overall Indian market. On one hand, along with the fast food sector emerging in parallel, modern chains may introduce a wider variety of processed foods, which tend to be energy-dense, and nutrient-poor[122]. However, these outlets also provide access to nutrient-dense foods such as fruits and vegetables, and compared to traditional shops, may provide a wider range of produce, that is higher-quality and safer, and with more consistent availability throughout the year[122,123]. Additionally, modern retail outlets may charge lower prices than traditional local shops[122,124]. As this market grows, these features may contribute to the finding that urbanisation and increasing incomes tend to increase diversity of diets, in terms of intake of both healthy and unhealthy foods, as well as overall dietary energy intake[125].

1.8 Setting of project: relevance of sustainable diets in India

India has high rates of undernutrition (including one-third of the world's cases of child stunting) coinciding with growing rates of overweight (about 20% among adults) and NCDs (9% of adults with diabetes, and 25% with high blood pressure)[126,127]. Monthly per capita expenditure (MPCE), an indicator of standard of living, has grown substantially in India in the last two decades[128], along with rates of urbanisation[129]. These trends are thought to be driving the nutrition transition in India: a shift away from staple foods, such as pulses and coarse cereals, to vegetable- and animal-based fats, refined cereals, and energy-dense, highly processed foods[130-132]. The health effects of these trends have been documented in the overall higher NCD prevalence rates in urban than rural settings[132,133], as well as the temporal pattern of increased rates of NCDs when rural residents migrate to cities and adopt urban dietary and lifestyle behaviours[134]. The evidence on socioeconomic inequalities and NCDs in India remains somewhat mixed, with lower-income groups more likely to experience cardiovascular disease[135], and higher-income groups having higher prevalence of diabetes[135] and hypertension[136]. As incomes continue to rise and India becomes increasingly urbanised, diets are projected to both diversify nutritionally with higher intake of fruits, vegetables, and animal-based products, while simultaneously resulting in higher nutrition-related health risks from excess dietary energy, oils, salt, and sugar[137,138].

While relative GHG emissions per capita are low in India compared to HICs, the country contributes the 4th highest amount of absolute emissions globally, and has set targets to reduce emissions by 33-35% (from 2005 levels) by the year 2030[139]. Indian agriculture's proportion of all GHG emissions has been steadily declining since the 1990s, due to the faster pace of growth from industry and increased energy use[140-142]. However, absolute emissions from agriculture are increasing, and the sector still contributes about one-fifth of national GHG emissions[141,143]. Additionally, while emissions from the world's major emitting countries, including China, have plateaued in recent years, India's are rising significantly[144].

Irrigation in the Indus and Ganges river basins contributes to 25% of the global blue WF related to agriculture[27], however, the amount of available freshwater used in Indian agricultural production is at high and potentially unsustainable levels. Agricultural irrigation accounts for 90% of freshwater use in the country, alongside depleting groundwater reserves in some regions[19,145]. Less than half of cropped area in India is irrigated[146], and therefore due to increasing water scarcity, there may be limited capacity for widespread expansion of irrigation to improve yields and agricultural efficiency.

Land use for agricultural production is also currently constrained. The amount of sown crop area has been stagnant over the last decade, and with rising urbanisation and development competing for available land, there is little capacity to increase agricultural land area[110]. Additionally, a substantial portion of current agricultural soil is considered degraded to some extent[146]. Lastly, both land and water resources are anticipated to come under further pressure with growing agricultural demand from population growth and changing diets[147-149].

When work on this PhD project first commenced, there was only one available study on sustainable diets in India[150], that compared the GHG emissions of a set of common foods in the country versus a hypothetical sustainable dietary basket. Although providing a useful starting point, the work did not use dietary intake data to assess actual estimated intakes, and did not provide any regional or national representativeness. Since that work, three recent analyses have been added to the body of literature: one using a case study of impacts on GHG emissions, land and water use at the city level in New Delhi[151], another focusing on water use and GHG emissions from shifting to healthy diets among rural-urban migrants in four Indian states[152], and a nationally-representative analysis modelling the impacts on GHG emissions of a healthy diet[74].

Given the multitude of modelling options possible for sustainable diet analyses (further details in Chapter 2), the lack of nationally-representative work using a number of environmental indicators, as well as assessments of affordability, there exists a gap in the literature on better understanding the context and opportunity for healthy and environmentally sustainable diets in India.

1.9 Project aims

The overall aim of this project was to estimate the environmental impacts and cost of healthy dietary shifts in the unique context of India, which faces high levels of both undernutrition and overweight/obesity, and agriculture-related environmental challenges.

More specifically, the objectives of this project were to:

- Systematically review the types of sustainable dietary patterns studied in the literature, and their impacts on a range of environmental indicators, to identify suitable sustainable diet types for analysis (**Paper 1**)
- Compare available dietary data sources in India to understand their suitability for sustainable diet analyses (**Paper 2**)
- Evaluate the environmental impacts, across a number of indicators, of dietary shifts in India; specifically a shift to healthy diets, and a 'business as usual' shift to affluent diets (**Paper 3**)
- Assess the affordability of healthy and sustainable diets in relation to current baseline diets (**Paper 4**)

1.10 Project structure

This PhD project is structured according to the research paper style thesis format. This section describes the purpose of each of the four papers included in the thesis, and their linkages with each other.

The **first paper** (Chapter 3) was a systematic review of the environmental impacts of shifting from current average diets to sustainable diets[25]. The purpose of this paper was to synthesise the available evidence and better understand the sustainable dietary scenarios that could be used in the main analysis of the PhD project. When the PhD commenced, there was an early and growing body of evidence on the environmental benefits of shifting to alternative diets. However, there was major heterogeneity between studies, including that due to country or region of focus, environmental indicator assessed, source of underlying dietary and environmental data, as well as a wide spectrum of potential sustainable dietary patterns (i.e., vegetarian diet, Mediterranean diet, replacing ruminant meat with poultry, etc.). There was therefore not a clear typology of the possible array of sustainable dietary patterns, their relative potential for reducing environmental impacts, or the possibility of trade-offs between environmental indicators. Based on the review, it was decided that national dietary guidelines (which could achieve a median reduction between 6-20% in GHG emissions, land use, and water use) would be the most suitable sustainable diet type to be used in the context of India, as these guidelines are already promoted through public health efforts, would be most culturally appropriate and realistic, and most sensitive to the various nutritional challenges in India.

The **second paper** (Chapter 4) was a comparison of dietary data sources available in India[96], with the aim of helping to select the dietary dataset to be used in the analysis and to understand its implications. Early scoping in the PhD highlighted two potential dietary data sources: India's National Sample Survey (NSS), a food expenditure survey, and the Indian Migration Study (IMS), a sub-national health survey. Both datasets provided relatively large sample sizes, but included quite different demographic samples. The NSS is nationally-representative, and the IMS focused on a sample of rural-urban migrants, largely in 4 out of India's 36 states. Alternatively, as the NSS uses a household-level format and records food purchases rather than actual intakes, there was an informal hypothesis that IMS's individual-level food frequency questionnaire (FFQ) would be a higher quality dietary data source. Surprisingly, given the long use of NSS data in nutritional analyses, no studies could be found that assessed its reliability against other sources, even in the context of a relatively large literature comparing dietary survey types[153-157]. The key aim of the paper was therefore to compare food consumption patterns in the NSS among a variety of available dietary data types; food balance sheets, 24-hour recalls, FFQ, as well as a separate national expenditure survey: the India Human Development Survey (IHDS). Environmental impacts of dietary shifts are often driven by changes in key food groups (animal-based foods, and their substitution with important nutrient-rich groups such as fruits and vegetables), and changes in absolute food intake. Therefore, the analysis assessed relative differences in intake of total quantity of food and major food groups, across 12 available data sources in the country. Ultimately, the NSS was chosen as the dietary data input for the later sustainable diet analyses; its national scope captured the various nutritional challenges in India, it showed relative consistency with the separate national expenditure survey, was among the most recently available data for India, and directly included household food price data, which would not otherwise require linking from an external source.

Note on additional work not presented in this PhD thesis: The above analysis had cleaned and converted a number of datasets into a format to enable estimating intake of individual food items and food groups; the cleaning of the IMS and NSS data was then used in several other analyses to which I contributed[99,152,158,159]. Separately, a similar effort was undertaken early in the PhD to obtain necessary GHG footprint data, including a literature review for secondary data, and scoping of methods for directly calculating footprints, given the lack of data specifically for India. Ultimately, collaborators at the University of Aberdeen undertook the generation of new Indian GHG emissions data for a number of food items, to which I contributed[160].

The **third paper** (Chapter 5) is the first of the main results papers of the PhD. It assessed the environmental impacts of dietary shifts in India, using two scenarios: adoption of diets meeting recommended dietary guidelines (as outlined in **Paper 1**) that were optimised using non-linear programming, and comparing this to a simplified nutrition transition scenario, in which diets of affluent households were adopted nationally[102]. The work is based on the dietary data derived in **Paper 2**. Given various environmental pressures facing India, the aim was to explore whether healthy dietary shifts in India could offer environmental benefits, as is shown in much of the literature in HICs.

The **fourth paper** (Chapter 6) assessed the costs of observed healthy and sustainable diets in India, in relation to average current diets, to explore the affordability of improved diets. This followed the results in **Paper 3** that shifts to dietary guidelines could provide environmental benefits in some cases (namely as a result of dietary change from those in India who currently consume above recommended dietary energy intake). Observed healthy and sustainable diets were chosen as the unit of focus in this paper, as opposed to the hypothetical optimised diets in **Paper 3**, for two reasons: one is that observed diets are realistic (as people have self-selected them), and therefore potentially more policy-relevant. Additionally, an analysis with a similar scope was published during my work on **Papers 3 and 4**, which had optimised hypothetical affordable and healthy diets in India (Rao et al., 2018)[74]. While many aspects of the approaches are different between my work and that of Rao et al., (I use three environmental indicators to categorise sustainability, while Rao et al. only focus on GHG emissions; we use different formats of the national dietary expenditure data, etc.), it was decided to further differentiate the work by retaining a focus on the costs of observed, rather than optimised, diets.

2. Background: methods in sustainable diet analyses

The study of sustainable diets is a relatively new field of interdisciplinary analysis, and one in which the approaches and methodology are highly varied, and still evolving. The following background section on methods describes the major approaches to assessing the environmental impacts and costs of sustainable diets, and structures it according to the main components of such analyses: choosing a sustainable diet scenario to compare against a baseline average diet; the dietary and environmental data inputs required; and the analytical approaches to then measuring the environmental footprints and costs of sustainable diets.

2.1 Selection of sustainable dietary scenarios for assessment

While the definition of sustainable diets proposed by the FAO encompasses health, environment, affordability, and socio-cultural considerations, much of the work to date has focused on the environmental benefits of population shifts to sustainable diets[38]. The types of research questions asked by sustainable diet analyses are varied, and include: to what extent will the adoption of a hypothetical sustainable diet scenario (with varying degrees of assumed healthiness or environmental considerations) affect environmental footprints?; how much do diet-related environmental footprints differ between observed diets in a population, and can these differences inform recommendations for a sustainable diet?; and, can a modeled diet that meets certain health and environmental thresholds still be realistic? To service this broad set of questions, many types of sustainable diet scenarios have been identified and assessed in the literature, and a number of the major types are presented in Table 1 below (though this list is not exhaustive and other iterations of these diets have also been proposed).

Table 1: Types of sustainable diet scenarios assessed in the literature.

Vegan
Vegetarian
Mediterranean
Pescatarian
New Nordic Diet
Meat from ruminant animals replaced with meat from monogastric animals
Meat reduction, replaced by plant-based food groups
Meat and dairy reduction, replaced by plant-based food groups
National dietary guidelines
National dietary guidelines further optimised for environmental benefits
Restricting excessive dietary energy intake

As outlined in the table above, sustainable diet types form a wide spectrum, though generally focus on reductions in some form of animal source foods, and replacement of these with plant-based foods. The proposed sustainable diets have varying degrees of prevalence in populations, and additionally, while it is principally the environmental impacts of sustainable diets that are directly assessed in studies, the sustainable diet scenarios examined usually assume *a priori* some degree of healthiness. To facilitate summarising a quite heterogeneous, yet overlapping, set of scenarios, I will loosely categorise sustainable diet types according to the degree of their anticipated healthiness and/or environmental benefit as presented in the studies in which they are used. For example, on one end of this spectrum, scenarios such as replacing ruminant meat with meat from monogastric animals like pigs or chickens[48,161-163], or replacing wheat and rice with root crops[164], are more so based on assumed environmental benefits rather than health considerations.

Other scenarios such as restricting excessive dietary energy intake[165-168], or vegetarian[26,169-175] and vegan diets[48,171,172,176-179], or reduced-meat diets supplemented with plant-based foods[94,165,180,181], have intended health benefits (i.e. reducing overweight/obesity, and promoting intake of fruits and vegetables), as well as some assumed environmental benefit (as meat production is known to be a major driver of agricultural footprints). However, the definition of vegetarian and vegan diets can differ between studies, as some are based on dietary guidelines[26,163,169,176,178,182], while others are based on existing, observed vegetarian diets that may not necessarily be comprehensively healthy[161,170,183,184]. Scenarios that reduce meat and replace the dietary energy with other foods also differ on what the replacement foods are, including plant-based foods[94,180,181,185], other animal source foods (dairy)[94,165], or a mix of both[165,167,186,187]. A number of studies have modeled a reduction in meat intake, without substituting this with any other foods[188-190]. While these analyses are a useful starting point to highlight solely the environmental impact of meat in the diet, they may be less realistic as the reduction in dietary energy would likely need to be compensated with other foods.

Other proposed diets are more comprehensively health-oriented, such as eating according to national dietary guidelines[85,169,176,191-193], or other guidelines primarily designed for health benefits, such as Harvard's Healthy Eating Plate[178] or the Dietary Approaches to Stop Hypertension (DASH) diet[81]. Mediterranean diet scenarios are primarily health-oriented, but also include cultural considerations[26,182,194,195], and the

New Nordic diet was designed to include health, cultural, as well as environmental considerations[84,196]. Similarly, another common dietary scenario with explicit health and environmental goals is using national dietary guidelines as a starting point, with further food group optimisation to reduce animal source foods (and presumably environmental footprints), while keeping the diet within nutritional requirements[179,196,197]. More details on mathematical optimisation are outlined in section 2.4 below.

The degree of healthiness of sustainable diets is usually defined as a threshold of meeting a set of dietary guidelines, while some studies also assess healthiness as a continuum measured through a nutritional index[81,191,198]. Of studies that report on the details of how they define healthiness, a wide variety of criteria are used across macronutrient, micronutrient, or food group-based guidelines. For example, some use almost exclusively food group-based[85,150] or micronutrient-based guidelines[191], while others use a combination of macronutrient and food group-based requirements; within these, some studies specifically include fruit and vegetables[42,173] while others do not[76]. Studies also differ on whether they include limits on total dietary energy.

The various sustainable dietary patterns proposed and assessed in the literature share many characteristics. These include increased intake of fruit, vegetables, and fibre, and reduction of processed or energy-dense foods, sugar, refined cereals, and animal source foods (to various extents). However, recommendations on some elements such as dairy, meats, fish, and vegetable oils can vary between different sustainable dietary patterns. For example, healthy dietary guidelines recommend low amounts of vegetable oils, and moderate amounts of meat, dairy, and/or pulses, and adherence to healthy guidelines can be achieved both with and without inclusion of meat. A Mediterranean diet limits meat intake, and in addition to a focus on fruit, vegetables, legumes and nuts, recommends high intake of vegetable oil (specifically olive oil) and fish[199]; a New Nordic Diet is relatively similar, with canola oil recommended instead of olive oil, and additionally, fruit and vegetables that are native to the Scandinavian region[200]. Pescatarian diets do not include livestock products, but do include fish and seafood. National healthy guidelines also vary across countries: for example, in the US, recommended dairy intake is higher than in other countries (at 700mL per person/day). This feature is estimated to lead to higher environmental impacts from adoption of dietary guidelines, versus average diets, in the US[168,178]. The overlaps and differences across sustainable diet types underlie some of the complexity in this research space, but also pose difficulties in producing consistent recommendations for key audiences such as the public and decision-makers.

Within this large diversity across the literature, using national dietary guidelines as a sustainable diet scenario is currently the most common approach[25]. This may be because they are already embedded as a public health goal, with dedicated health promotion efforts behind them, their recognition among the public, and their degree of cultural appropriateness, compared to other types of sustainable diets (e.g. vegan diets). Additionally, given the lack of global or national environmental targets related to agriculture and diets, dietary guidelines provide a clear and flexible framework, and a potential goal for both environment and health.

2.2 Dietary data to inform baseline and sustainable diet scenarios

Dietary data are a key input into sustainable diet analyses, as they provide a baseline average diet to which a sustainable dietary scenario can be compared to, and in some cases also serve as a starting point for constructing a sustainable dietary scenario. A variety of dietary data types are used for this purpose.

Most often, baseline dietary patterns are based on national-level dietary surveys[83,169,201] such as the National Health and Nutrition Examination Survey (NHANES) in the US[202], or the UK National Diet and Nutrition Survey (NDNS)[42,93]. These dietary surveys typically rely on multi-day food records, which are generally considered to be high-quality data relative to other dietary survey types. In other cases, sub-national dietary surveys such as the Indian Migration Study[152] and China Health and Nutrition Survey[203], or city-level data[76,174] are also used, which use a variety of recording methods, including weighed dietary records and FFQs.

Additionally, data can come from health-specific studies that utilised a dietary survey component, such as the Oxford[171], Norfolk[81] and Netherlands[94,204] cohorts of the European Prospective Investigation into Cancer and Nutrition (EPIC) study, or the Adventist Health Study conducted in the US and Canada[187,205].

Another source of data to estimate baseline population intake are food availability data, such as the FAO food balance sheets (FBS), and the US Department of Agriculture (USDA) loss-adjusted food availability (LAFA) data series. These data provide an estimate of the supply of food available for domestic consumption, taking into account production, imports, exports, non-food uses of crops, and wastage. They are frequently used for multi-country and global studies of sustainable diets as they provide a standardised way of conducting international comparisons. However, FAO food balance sheets typically overestimate supply[153,206], and this may have the effect of biasing the resulting environmental impacts if the comparison sustainable diet has lower dietary energy.

Others use an approach in which food availability data are combined with national dietary surveys. This has usually been to done better represent the full extent of environmental impacts of food production, as dietary surveys using a food record format may underestimate intakes, and/or do not include any purchased food that was wasted by the consumer, or food losses occurring before reaching the consumer. Therefore, studies using this approach start with the intake of food groups as recorded in the dietary surveys, and scale these up proportionally to match the total per capita dietary energy availability provided in FBS[161,168,170], or infer the amount of wastage in the food system from comparing the two data sources[181]. Other studies using this approach do not provide a description of how or why the two sources are combined[84,175,207].

Household consumption and expenditure surveys (HCES) are rapidly growing sources of data in LMICs. They are typically conducted to measure various aspects of poverty, development, and calculation of consumer price indices[208]. Their design is not usually intended to specifically assess dietary and nutritional outcomes, though they are increasingly used for such purposes, as they often contain rich data on food acquisition and consumption, and are often the only national source of data in

LMICs; currently almost 100 countries have implemented at least one round of a HCES[209]. Apart from the work in this thesis, only one other study has been found to use a HCES in the assessment of sustainable diets[74]. However, this likely largely reflects the lack of sustainable diet assessments in LMICs. Limitations of these surveys, depending on their format across countries, is the need to make assumptions on intra-household food distribution and individual-level intake, a potentially long recall period, and the quality of data on foods prepared and eaten outside the home[208].

Dietary data can also be used to inform the creation of a baseline food basket[79,85,182] (with the comparison sustainable food basket constructed based on principles of sustainable eating, such as reducing animal source foods), which may better reflect the dietary habits of a household or family, and facilitate matching to income data to measure diet affordability (more details on this are provided in Section 2.5).

2.3 Environmental data

Generating environmental footprints of dietary patterns requires underlying environmental impact data for the food items or food groups making up the dietary pattern. For example, to estimate the total WFs of eating a diet of three kilograms of carrots and two kilograms of beef per day, one would first need data on the separate per kilogram WFs of producing carrots and beef. The sources and methods of generating these data differ by the type of environmental footprint, and are described below for GHG emissions, WFs, and LU.

Data on GHG emissions (measured as the quantity of equivalent carbon dioxide emissions per kilogram of food, or kg CO_2eq/kg) of food production come primarily from life cycle assessments (LCAs). LCA is a method of comprehensively estimating the environmental impacts from a product across its life cycle. LCAs assess all inputs and outputs for various stages of production of an item, and measure the resulting environmental impacts, such as GHGEs, energy use, or eutrophication[210]. LCAs may have different system boundaries, meaning that they are conducted across various stages of a product's life cycle: for example, for a food item, these could include agricultural production and primary processing (such as cleaning or trimming), or may go further, to also include distribution to retail centres, storage, and measure the resources used in transport and food preparation done by consumers. A given food item may have a variety of impact estimates calculated for it across different LCAs, as many factors may affect the ultimate footprint calculated, including the region of production, types of production systems (intensive or small-scale), as well as different assumptions about each life cycle stage, and how related products are weighted and dealt with (e.g. the relative values of milk, meat and leather from a cow). Primary LCA data for each of the food items/groups making up a dietary pattern may be generated for a study[94,169,170,198,207,211], though as this is a labour-intensive effort, LCA data can also be gathered from published or grey literature[93,165,182,191,202,212], or come from a combination of both[158,187]. The major greenhouse gases emitted through agricultural production are carbon dioxide, methane and nitrous oxide, and each has a different half-life and global warming potential; thus the CO_2eq metric standardises the impacts of each, and allows for comparison across studies.

A WF is a measure of the amount of fresh water used to produce an item, usually in the units of m^3 of water per kg of product. Almost all WF data used in sustainable diet analyses comes from a major database provided by the Water Footprint Network, who have both developed the global standards for WF measurements, as well as created an open-access dataset of WFs by crops and animal products, for most countries, globally[27,213]. WFs for crops are calculated using a global spatial-grid water balance model that considers a crop's water requirements, actual crop yields by region, local climate and soil factors, and rates of fertiliser use. WFs for animals are then a function of the water used in production of crops for animal feed, and the direct water used for drinking and other services such as livestock cleaning and housing. The difference in WFs between animals is mostly reflected by differences in feed conversion efficiency, and the amount, composition, and origin of feed. While the WFN data are the major source of WF values for sustainable diet analyses, some studies rely on other secondary data on WFs from other published and grey sources in the literature[76,194,214]. While WFs show the absolute water requirements, a limitation is that they do not reflect the environmental impact of that water consumption across water-scarce and water-abundant regions, and a water scarcity-weighted footprint approach has been suggested[215] – though both approaches are useful for answering different questions on water use[216].

Land use, similar to WFs, is a measurement of the amount of land required to produce a crop or product (m^2 per kg of product). The type of land can be either arable (for temporary crops), or under permanent crops or permanent pastures. Land use is typically derived directly from data on crop yields (e.g. how much wheat is grown per hectare, in a given country/region), or where such data are not available, calculated by dividing the quantity of production by the amount of area harvested for a given crop[217]. These data are generated by individual studies, or collected through national agricultural statistics. FAO's Statistics Division aggregates these data and through the FAOSTAT database provides comprehensive yield data globally for 173 crops (though information on all crops is not available for all countries)[116,217]. For studies that report on the source of their land use data, they typically use the FAOSTAT source or national agricultural statistics[26,167,184,191,193,194,218], or otherwise secondary data from a review of the literature[219], existing land use models or LCA software with own data[181,220,221], or proprietary data[94,169,196].

Environmental footprint values can differ substantially between food items, and different production systems as well as production in different climatic zones can also yield highly variable footprints for a given food item[17]. Therefore, a study would ideally aim to calculate their own environmental impacts, or gather secondary data from the literature, for all individual food items making up a diet, and for the source country of where those items are produced (rather than consumed). Regarding environmental impacts data for individual food items, a major limitation is that generating such an array of data is highly time-consuming and usually requires specialised environmental knowledge, and secondary data from the literature are almost always not available for all food items captured in the dietary data. When environmental data for food groups or food items are missing, studies often assign proxy values to the missing food groups, based on other food items or groups (e.g. using data on environmental impact of apples for pears), or an average of other food items. This is often done based on similarity of nutritional food group type (i.e., values for corn used as a proxy for millet, or value of a root crop being used for another root crop). While this can foreseeably lead to some inaccuracies in footprint measurements of diets, recent studies have shown that using these simplified proxies still yields valid results[202,222]. This is likely because the differences in environmental footprints between the main food groupings of ruminant meat, non-ruminant meat, and plant-based foods, tend to be larger than any within-group variability. An additional complexity is that of matching appropriate environmental footprints to meals or processed food items, made up of a number of individual food items. In this case, environmental data for processed and packaged foods are sometimes available, or otherwise, recipe or composition data are required to disaggregate the food into individual components, and match the environmental footprint data accordingly. Regarding the issue of environmental impacts of food varying by country of production, most studies assume that food is grown in the same country as consumed (though in reality there is a varying degree of importation of foods, depending on the country of focus), and aim to gather data accordingly - though in practice, data availability restrictions also mean that environmental data from a mix of countries is matched to the food items within a diet. To what extent this can impact results, has not been well studied.

2.4 Analytical approaches to comparing environmental footprints between diets

As outlined in section 2.1, the sustainable diets literature asks a range of research questions, and uses a variety of different sustainable diet scenarios in the process of attempting to answer them. However, across all of these, a number of common steps are required in the analyses. Once a research question and scenario are framed (e.g., what would be the environmental impacts of adopting pescatarian diets in country X – described in section 2.1), a sustainable diet with the requisite types and quantities of food items must be constructed, and subsequently, the outcomes of interest need to be compared between the baseline and sustainable diet. In this section I describe common approaches to both these latter steps.

Sustainable diet scenarios often, but not always, include underlying nutritional considerations, and the approach to constructing the dietary scenario depends in part on these. For example, if food-based dietary guidelines are used (such as 50 g per day of pulses, 100 g of fruit, etc.), then the sustainable scenario can be directly drawn from these. If using any macro- or micronutrient considerations, nutritional composition data (from available food composition tables for the relevant country) need to be linked to the individual food items or food groups, and the food items or groups then need to be weighted and balanced to meet the nutritional considerations. This balancing can be done manually, for example in a spreadsheet, or through the use of mathematical optimisation. Optimisation is a mathematical modelling technique, using an algorithm to solve a given problem defined as a series of equations. This includes specifying a main objective function to minimise or maximise, with the addition of any other constraints that must be met. An example of such a model could be solving for the quantity of each of 40 individual food groups in a diet, that will minimise the amount of dietary energy, while meeting requirements for at least 400 g of fruit and vegetable intake, and no more than 5 g of salt. Other objective functions can be designed to, for example, minimise the cost of the diet, or minimise the overall deviation of food group intake from the baseline diet. Models can be linear or nonlinear, depending on the form of the equation of the objective function and constraints. The solution that is found using a linear programming model is the best value that can be found for that objective function, while nonlinear programming models may generate different solutions depending on the starting values[223]. Optimisation can be performed in a dedicated dietary software (e.g. Optifood), a statistical software such as R, or with the specialised Solver tool in Excel.

Studies also differ in whether they choose to compare baseline and sustainable diets which are isocaloric (containing equal amounts of dietary energy). Average diets in HICs often include excess dietary energy, and therefore if the sustainable diet is not isocaloric, it will typically include less dietary energy than the baseline diet. Comparisons which are isocaloric allow for isolating out specifically how the change in types of food groups consumed affects environmental footprints; while for studies not using an isocaloric comparison, the difference in environmental footprints between diets will be a function of both the change in food types eaten, as well as the overall quantity of food consumed.

Once a sustainable diet is modelled or constructed, its environmental footprints or cost are calculated. This is often a case of simply multiplying the quantity of each food group or item (e.g. 2 kg of carrots consumed per day) by that item's environmental footprint (e.g. production of one kg of carrots results in 0.5 kgCO_2eq), and summed across all foods in the diet; or similarly, for dietary cost, the quantity of each food item is multiplied by the price of that item, and summed across all foods to derive the final dietary expenditure (additional details on measuring cost and affordability are in section 2.5, below). Total footprints or costs between the baseline and sustainable diets can then be compared in relative or absolute terms.

Another method to model changes in environmental impacts from dietary change, used in a number of studies, is environmentally extended input-output analysis[75,85,176,183]. This method is an macroeconomic approach that models the flow of goods between major economic sectors. Taking a top-down approach, it uses data on environmental inventories for whole sectors and major commodity groups within sectors (e.g. meat production, within agriculture). However, as the model is aggregated at the level of major sectors and product categories, it may not provide enough granularity to model changes in consumption and footprints of individual food items (such as differentiating chicken, pork and beef within a meat production category)[224]. As input-output analysis typically covers production and not downstream stages such retailing, it can be combined with a process LCA approach to add these other food value stage footprints[224].

As an alternative method to choosing and constructing a hypothetical sustainable dietary scenario as above, some studies stratify individual observed diets within dietary surveys, and compare various sustainability indicators across these. This is done by, for example, stratifying individuals into quartiles of diet-related environmental footprints[202] or healthiness[81], assigning individuals into a binary higher- or lower-than-average sample footprints category[83], using an ordinal scale of quantity of meat intake[171], or stratifying population intakes into distinct dietary patterns using modeling[158], and comparing the differences in dietary footprints across these groupings. The benefit of this approach is that those diets which are identified as more sustainable may be more realistic than hypothetical scenarios, as they are already self-selected diets.

A major limitation in the field is the lack of a standardised approach to measuring uncertainty in environmental impacts of diets. Most underlying environmental data are produced as a point estimate (for example, the LU of a wheat crop in a given country is often simply a measure of total wheat harvest recorded by the country, divided by the area harvested for wheat[225]), and do not contain standard errors or a range of uncertainty. To date, a very small number of studies have attempted to generate uncertainty ranges, through various approaches. Where studies use secondary environmental impact data gathered from the literature, and obtain several estimates for a given food product (i.e., values of 0.5, 0.1, and 0.3 kg CO_2eq per kg of carrots), it is possible to create a probability distribution from these values, which are then used in a Monte Carlo model, that runs a number of iterations of the diet-related environmental impact calculations, each time using a random value from the environmental data distribution; these multiple iterations then create a sample of estimates, from which a confidence interval can be generated[165]. Alternatively, when a given environmental dataset contains other measures of variance, such as a national-level WF for carrots, as well as WF estimates among sub-national regions, this variability can also be fed into a Monte Carlo analysis[152]. Another approach when multiple footprint estimates are available for a given food item, is to use the mean of these, as well as the lowest and highest value, to derive a respective mean with a lower and upper bound in the dietary footprint calculation[202] (e.g. similar to the above example, if there are available estimates of 0.5, 0.1, and 0.3 kg CO_2eq per kg of carrots, and a dietary pattern consumes 2 kg of carrots, then the environmental impacts of that diet would be 0.6 $kgCO_2eq$ with a lower and upper bound of 0.2 and 1.0 $kgCO_2eq$).

The above approaches use the uncertainty from environmental data, though a full measure of uncertainty would also include that from the underlying dietary data, as well as the nutritional composition of food data, if available. One study to date has attempted using two such levels of uncertainty, through the use of Monte Carlo simulations, each time sampling randomly from the distribution of both dietary intake and environmental data[152].

2.5 Measuring affordability of sustainable diets

There are two ways to assess the affordability of diets: absolute affordability measures the proportion of a household's income that a diet takes up, and only one study on sustainable diets to date has been found to use this approach[79] (though the literature on healthy diets, without environmental considerations, has more examples[64-66]). Alternatively, many studies use a relative measure of affordability that compares whether a given diet costs more or less than another diet[78,80,81,83,84,86]. For example, relative affordability is used in studies using self-selected diets to compare mean costs across quartiles of diet-related healthiness or environmental footprints, as well as studies that compare dietary cost between an average current diet and a hypothetical sustainable diet.

Additionally, another set of work assesses relative affordability in a more indirect approach, by using mathematical optimisation to assess whether it is possible to create healthy and lower-footprint diets within a cost threshold (usually the threshold is to match the cost of a current average diet). This approach is used to assess what the resulting sustainable diets would look like, and how divergent they would be from current average diets[74-76].

Measurement of both absolute and relative affordability requires data on the prices of individual foods, which are then linked to dietary patterns to calculate dietary cost. These data are obtained from secondary retail price data[74,81,86], collection of primary data through price surveys at markets or retail outlets[76,79], or HCES[74] which provide the quantity of food purchased for a household and the associated expenditure. Calculating absolute affordability additionally requires data on household incomes, available from national household surveys[79]. The threshold for absolute affordability, above which the price of the diet would pose an unreasonable burden, has been proposed as 30%[66]. Studies measuring absolute affordability use dietary intakes in the form of a food basket to meet the needs of a hypothetical family or household over a set duration of time. This format can then be linked to average incomes for dual- or single-income families, as appropriate. Compared to an individual-level analysis, this format better represents income and purchasing dynamics in households[58]. Given the additional information required for measuring absolute affordability, most studies use the relative affordability approach. However, with the relative approach, a finding that a sustainable diet is cheaper than an average diet does not necessarily indicate that the cost is equitable or fair, or would allow individuals to maintain the sustainable diet in the long-term.

2.6 Summary of methods in this project

Among the diversity of approaches and inputs outlined above, here I briefly summarise the methods used in this project.

Dietary data

From the several data sources available in India, my project uses the NSS HCES. The scope of the NSS is to collect, among other indicators, quantitative data on household food consumption[226], and therefore compared to other HCES globally, the features of the NSS may be somewhat more suited to determining nutritional and food intake patterns. These include a long and comprehensive list of food items purchased for in-home consumption, a set of survey questions on out of home consumption, and a recently updated survey format with a shorter recall period for nutrient-dense foods, which may improve recall accuracy.

The NSS is designed to be a representative sample of households in India, covering almost the full geographical area of the country (excluding areas inaccessible due to terrain or weather, or those experiencing conflict), and using a stratified random sample. In brief, across all Indian states and union territories, an inventory is taken of villages and blocks (sections) of urban areas. A subset of these total national units are then chosen for sampling within the NSS, with careful selection to represent socioeconomic, geographic, cultural and religious diversity, while also balancing available survey resources (in the 68th round, almost 12,800 units across the country were chosen). Within each unit, a set of eight households are selected for surveying[226,227]. Additionally, the overall sample is divided between four sub-rounds during the year to capture seasonality, with each of the sub-rounds being representative of the national village and urban block units described above.

Using the NSS questionnaire instrument, field workers survey a respondent for each household. As field work is done during the day, the respondent is typically the female adult of the household, who recalls other household members' intake. Individuals without a formal residence are excluded from the survey, though in some contexts, individuals or families permanently or semi-permanently residing in unconventional accommodation such as open spaces, roadside shelters, or under bridges are included in the sample.

Compared to FAO FBS for India, which provide per capita estimates of food availability at the national level, the NSS HCES allows for examining consumption by sub-national regions and demographic variables. It additionally already includes expenditure data, and while these again depend on recall accuracy, they are directly available for each household in the survey, and therefore provide more granular data than other available consumer price surveys. Further details on the choice of the NSS compared to other sources are described in section 1.9.

The NSS described above is the dietary dataset used in the two research papers assessing the environmental impacts of shifting to healthy diets, and the cost of healthy and sustainable diets (Chapters 5 and 6). My methods paper (Chapter 4), compares a number of Indian dietary data sources using varying dietary data formats: FBS, 24-hour recalls (24HR), and FFQs. I briefly outline the methodology used in these survey formats below, while the specifics of the datasets themselves are outlined in the paper (Chapter 4).

Both 24HR and FFQs are survey formats that directly measure intake at the individual level, while FBS estimate individual intake from national-level data. The two former sources are generally viewed as more accurate intake estimates than national or household-level data, while 7-day weighed food records remain the gold standard for assessing dietary intake[228].

The **24HR** method uses a trained interviewer who leads a respondent in recalling the quantity and type of food and drink consumed over the previous 24 hours. The interview is semi-structured to aid the respondent in remembering as much as possible, including prompting about different periods during the day, or activities undertaken, The recall may also be assisted by showing the respondent standard portion sizes, either physically or in photos or cards, to better estimate the quantities consumed. The assessment tool may also be adapted to be self-administered. Recall of intake from one day is often too narrow of a window to adequately represent an individual's usual diversity of intake, and therefore they surveys are repeated, where possible, over two or three days to improve accuracy[228,229].

FFQs are an instrument that includes a list of foods and/or meals, and questions relating to the frequency, and sometimes quantity, of intake of each item (such as number of times eaten per day, whether the item is eaten on a daily, weekly or monthly basis, and in some surveys, the portion size). FFQs typically use a broad recall timeline of several months or a year, and a respondent answers the frequency questions for those items which they recall have been consumed in that period. The questionnaire can be interviewer- or self-administered. The number and types of items in the food list should be specific to, and validated in, the study context, and the list can therefore vary depending on the research question, population, and region of interest, though will typically range from 10 to 200[229]. Both the 24HR and FFQs can be matched to recipe and food nutrition composition data to estimate nutritional content from the recorded intake. As they are retrospective methods, both may be prone to varying degrees of recall bias[228].

National FBS provide a picture of available supply of a large number of crops and animal-source products (~100) at the country level, by taking into account agricultural production, imports, exports, wastage, and use of products for non-food purposes. Average per capita intake in grams per person per day, for a given year, is estimated by dividing the national supply of items by the country population. These estimates are provided for most countries by the FAO, which annually compiles the country-level data directly from national ministries and statistical offices. However, country data for various products can be missing, or contain inaccuracies, and FBS are therefore also prone to measurement errors – often overestimating per capita intake[153]. Additionally, FBS do not represent well the level of home food production (more common in LMICs than high-income countries), or the extent of processing of the primary food commodities produced[228].

Sustainable dietary scenarios

Of the number of sustainable diet scenarios used in the literature, I assess the environmental impacts of national healthy guidelines, given that they may serve as a useful dietary goal across the diversity of nutritional challenges in the country. I calculate the environmental impacts of shifting current diets at the national level and among a number of sub-national samples – none of which currently meet healthy guidelines - to healthy diet scenarios. For this, I construct a healthy diet for each population sample using linear optimisation. This method allows for creating healthy diets that are as close to each of the current average diets as possible, potentially creating more realistic scenarios. In the final paper, I compare the costs of observed healthy and lower-footprint diets with average diets in the NSS sample. Using observed healthy diets allows for estimating the prevalence of these diets in the population, as well as assessing the current affordability barriers to adoption of the improved diets.

Environmental data

Data on WFs and LU of food items are drawn from the commonly used sources of the WFN[230] and FAO[116], while data on GHG emissions of foods come from a recent study that generated novel India-specific data for many food groups, combined with secondary data from across the literature[158,160]. The GHG values use a global warming potential timescale of 100 years, as is used in the Indian national GHG accounting data that the estimates are based on. Further details of these methods are described in each research paper, and suggestions for the improvement of methods and future work are outlined in section 7.4.

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RESEARCH PAPER COVER SHEET

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SECTION A – Student Details

Student ID Number	231894	**Title**	Mr
First Name(s)	Lukasz		
Surname/Family Name	Aleksandrowicz		
Thesis Title	Impact of dietary shifts in India on greenhouse gas emissions, land use, water use, and food expenditure: a nationally-representative study		
Primary Supervisor	Prof Sir Andy Haines		

If the Research Paper has previously been published please complete Section B, if not please move to Section C.

SECTION B – Paper already published

Where was the work published?	PLoS One		
When was the work published?	November 2016		
If the work was published prior to registration for your research degree, give a brief rationale for its inclusion			
Have you retained the copyright for the work?*	Yes	Was the work subject to academic peer review?	Yes

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SECTION C – Prepared for publication, but not yet published

Where is the work intended to be published?	N/A
Please list the paper's authors in the intended authorship order:	N/A

Stage of publication	Choose an item.

SECTION D – Multi-authored work

For multi-authored work, give full details of your role in the research included in the paper and in the preparation of the paper. (Attach a further sheet if necessary)	I designed the study protocol, reviewed the studies and extracted data, performed the analysis, drafted the manuscript, prepared and submitted the final version, and responded to peer reviewer comments.

SECTION E

Student Signature	[redacted]
Date	Apr. 2nd, 2019

Supervisor Signature	[redacted]
Date	2nd April 2019

The impacts of dietary change on greenhouse gas emissions, land use, water use, and health: a systematic review

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Abstract

Food production is a major driver of greenhouse gas (GHG) emissions, water and land use, and dietary risk factors are contributors to non-communicable diseases. Shifts in dietary patterns can therefore potentially provide benefits for both the environment and health. However, there is uncertainty about the magnitude of these impacts, and the dietary changes necessary to achieve them. We systematically review the evidence on changes in GHG emissions, land use, and water use, from shifting current dietary intakes to environmentally sustainable dietary patterns. We find 14 common sustainable dietary patterns across reviewed studies, with reductions as high as 70-80% of GHG emissions and land use, and 50% of water use (with medians of about 20-30% for these indicators across all studies) possible by adopting sustainable dietary patterns. Reductions in environmental footprints were generally proportional to the magnitude of animal-based food restriction. Dietary shifts also yielded modest benefits in all-cause mortality risk. Our review reveals that environmental and health benefits are possible by shifting current Western diets to a variety of more sustainable dietary patterns.

Introduction

There is an urgent need to curb the degradation of natural resources and to limit global warming to less than 2°C, while providing a nutritious diet to a growing and changing world population [1, 2]. Agriculture is responsible for up to 30% of anthropogenic greenhouse gas (GHG) emissions, about 70% of freshwater use, and occupies more than one-third of all potentially cultivatable land [2, 3], with animal-based foods being particularly major contributors to these environmental changes [4]. These impacts present challenges for improving global health and development, by exacerbating climate change, driving biodiversity loss and soil degradation, and increasing freshwater scarcity [2, 5]. At the same time, dietary risk factors are major contributors to the burden of non-communicable diseases through inadequate intake of fruit, vegetables, nuts and seeds, and dietary fibre, together with high consumption of red and processed meat [6].

The Rockefeller Foundation-Lancet Commission on Planetary Health suggested that there is major potential for dietary changes to improve health and reduce the environmental impacts of food production [2]. The United Nations Food and Agriculture Organization (FAO) defines sustainable diets as those which are healthy, have a low environmental impact, are affordable, and culturally acceptable [7]. A growing body of research has analysed the environmental impacts in high-income countries (HICs) of adopting diets that are proposed to lower the environmental footprint of food production, often referring to these as sustainable diets [8-11]. A variety of sustainable dietary patterns have been suggested, including vegetarian and Mediterranean, as well as following national dietary recommendations. Such diets may deliver health and environmental benefits due to partial replacement of animal products with plant-based foods [8, 12], and thus, adopting sustainable diets may play an important role in achieving a number of the Sustainable Development Goals (SDGs).

However, widespread policy action is lacking on integrating environmental and nutritional priorities [13]. This may be limited by the lack of collated data and clear summaries of the environmental and health impacts of shifts to sustainable diets – with the body of research using a variety of proposed sustainable diets, and most studies focusing on only one aspect of sustainability - and therefore uncertainty about the possible magnitude of impacts.

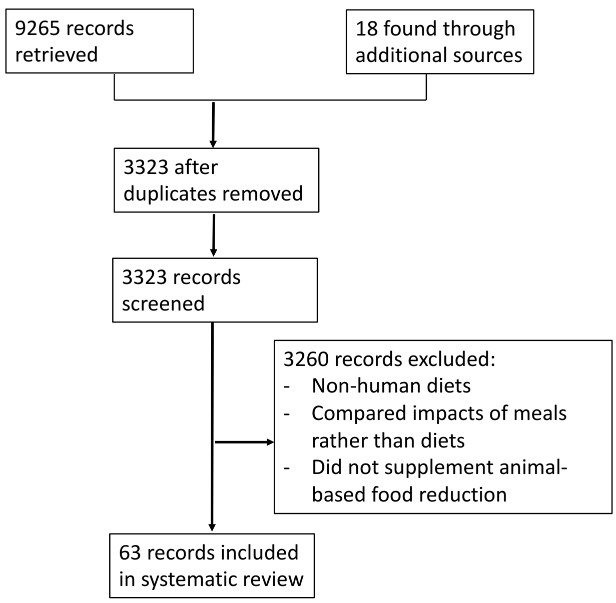
We systematically review the evidence of the impacts of adopting sustainable diets on GHG emissions, agricultural land requirement, and water use, and compare the environmental and health effects between various types of sustainable dietary patterns. Our analysis aims to substantially expand on two previous reviews [14, 15], as a large number of studies in this area have been published since then, and we also include grey literature, and the additional indicators of water use and health impacts.

Methods

Search strategy and selection criteria

We conducted a systematic review of studies measuring the environmental impacts of shifting current average dietary intake to a variety of proposed sustainable dietary patterns, and our review is current as of 10th June 2016. We followed PRISMA quality guidelines [16]. The environmental impacts we considered were GHG emissions, land use and water use. Scopus, ProQuest, PubMed, Web of Science, and Science Direct databases were searched for articles. Peer-reviewed studies with English-language abstracts from any region were eligible, as well as grey literature such as conference abstracts and reports. Studies were screened for inclusion independently by two reviewers (LA, EJ), and were reviewed for other relevant references (Figure 1).

Figure 1: Selection of eligible studies.



Inclusion criteria for studies were as follows: quantifying changes in GHG emissions, land use, or water use, between average population-level dietary intake and proposed sustainable dietary patterns; using dietary or consumer expenditure surveys, or food balance sheets to inform the baseline diets; and, using baseline dietary data from 1995 onwards. The three environmental indicators were selected based on an initial screening of available indicators in the literature. Studies were excluded if they evaluated the impacts of single food items or meals rather than dietary patterns, or used alternative diets targeting meat or dairy reduction without compensating for this decrease in energy intake with intake of other foods. Our literature search identified a related theme of research on carbon taxes, which have been proposed as a tool to reduce GHG emissions through influencing consumer food choice and therefore dietary patterns. We did not include these studies in our main analysis as the resulting diets did not fully align with the common dietary patterns found across all other retrieved studies. However, the discussion section summarises findings from the studies that investigated the effect of carbon taxes on dietary GHG emissions.

The following parameters were extracted from studies: country or region, year of baseline diet, methods and sources of environmental impact data, type of sustainable diet(s) measured, environmental impacts of baseline and sustainable diets, if GHG emissions included those from land use change, health impacts, degree of change for the sustainable diet (e.g., amount of meat reduction), whether sustainable dietary patterns were self-selected within studies (dietary patterns as eaten by study participants, as opposed to modelled or designed by study authors), and energy content of baseline and sustainable diets.

Analysis and quality assessment

Average population-level intakes in the reviewed studies were taken as the baseline diet, with each comparison between a baseline diet and a given sustainable diet categorised as an individual scenario. In each scenario, differences in environmental impacts between baseline and sustainable diets were quantified as the relative differences in carbon dioxide-equivalent GHG emissions (kg CO_2eq/capita/year, which is an adjusted indicator including CO_2, N_2O, and CH_4), land use (m^2/capita/year), and water use (L/capita/day). Where studies reported impacts in absolute amounts, we converted these to relative differences. Impacts were stratified by sustainable dietary pattern, and by environmental indicator. Environmental impact data using life cycle analysis (LCA) often do not include measures of variance, and therefore the reviewed studies did not provide confidence intervals for environmental impacts. Impacts did also not include systemic environmental feedbacks. Differences in environmental impacts between diet types were assessed using medians, and visualised using box and whisker blots. We converted any health effects originally reported in absolute terms to relative changes, by using appropriate population totals from the Global Burden of Disease Study [17]. We used a sign test to check if the number of instances where the direction of impact changed after adopting sustainable diets was statistically significantly different than what would be expected due to chance alone.

Study quality was assessed through three requirements: modelling the baseline diet on dietary intake surveys rather than food availability or expenditure; a description of the source and methods of the environmental impact data used; and that differences in the energy content of baseline and sustainable diets were within 5%. This latter cut-off was used as some studies aimed for an isocaloric design between compared diets, but due to modeling logistics, some minor caloric differences remained. These quality measures were selected since food balance sheets or expenditure-based surveys may differentially under- or over-estimate consumption of certain food groups [18], while the effect of not standardising calories may attribute environmental impacts to a reduction in absolute food intake rather than choice of food type. The potential for bias in the results was assessed by removing those studies that did not meet the above requirements, and using Spearman coefficients to compare the ranking of sustainable diet types before and after removal of studies, as well as a sign test for the direction of impact.

The review protocol, with additional information and specific search terms, is available in Supplementary document S1. Analyses were performed, and graphs made, using STATA version 14.

Results

A total of 210 scenarios were extracted from 63 studies. Of these, 204 scenarios were modelled on national-level diets in HICs, one on a city in a middle-income country, and five on global dietary patterns (Supplementary tables 1a-c) [8-11, 19-77]. Fourteen studies came from grey literature. Fourteen sustainable dietary patterns were proposed: vegetarian, vegan, pescatarian, replacing ruminant with monogastric meat, balanced energy intake, following healthy guidelines, Mediterranean diet, New Nordic diet, and meat reduction, with other sub-scenarios such as type of food supplemented by meat reduction, and healthy guidelines with further optimisation (Table 1). Several studies designed sustainable diets by starting with national healthy guidelines and optimised the balance of foods further, through linear programming [9, 11, 53, 56, 63, 66, 72, 75] or manually [32, 34, 38, 45, 54, 55, 59, 67], to generate additional environmental benefits; these scenarios have been termed “healthy guidelines plus further optimisation”. Balanced energy intake were scenarios where the average current diet was scaled down to recommended caloric intakes without changing the mix of food groups eaten. The category of meat replacement with mixed foods indicates dairy and plant-based food.

Table 1: Description of the number of reviewed scenarios, by type of sustainable dietary pattern and environmental indicator.

	Environmental impact		
Sustainable diet type	**GHG emissions**	**Land use**	**Water use**
Vegan	14	6	1
Vegetarian	20	7	9
Ruminants replaced by monogastric meat	6	3	1
Ruminants replaced by monogastric + no dairy	1	-	-
Meat partially replaced by plant-based food	8	4	-
Meat partially replaced by dairy products	3	1	-
Meat partially replaced by mixed food	7	1	-
Meat + dairy partially replaced by plant-based food	5	3	3
Balanced energy intake	6	2	1
Healthy guidelines	21	10	9
Healthy guidelines + further optimisation	16	5	4
Mediterranean	8	5	4
New Nordic Diet	3	1	-
Pescatarian	6	4	2
Total	124	52	34

Of the 210 scenarios, 197 showed a reduction in environmental impacts when switching from baseline to alternative dietary patterns (sign test: $p<0{\cdot}0001$), while thirteen scenarios showed an increase or no impact. The median changes in GHG emissions, land use, and water use, across all sustainable diet types, were -22%, -28%, and -18%, respectively. The largest environmental benefits across indicators were seen in those diets which most reduced the amount of animal-based foods, such as vegan (first place in terms of benefits for two environmental indicators), vegetarian (first place for one indicator), and pescatarian (second and third place for two indicators).

The ranking of sustainable diet types showed similar trends for land use and GHG emissions, with vegan diets having the greatest median reductions for both indicators (-45% and -51%, respectively), and scenarios of balanced energy intake or meat partly replaced with dairy, having the least benefit. Although the water use scenarios had smaller sample sizes, they showed somewhat similar trends across sustainable diet types, with vegetarian diets having the largest benefit (median -37%), though with the notable exception of the single vegan scenario showing an increase in water use (+107%) (Figures 2-4).

Figure 2: Relative differences in GHG emissions (kg CO_2eq/capita/year) between current average diets and sustainable dietary patterns.

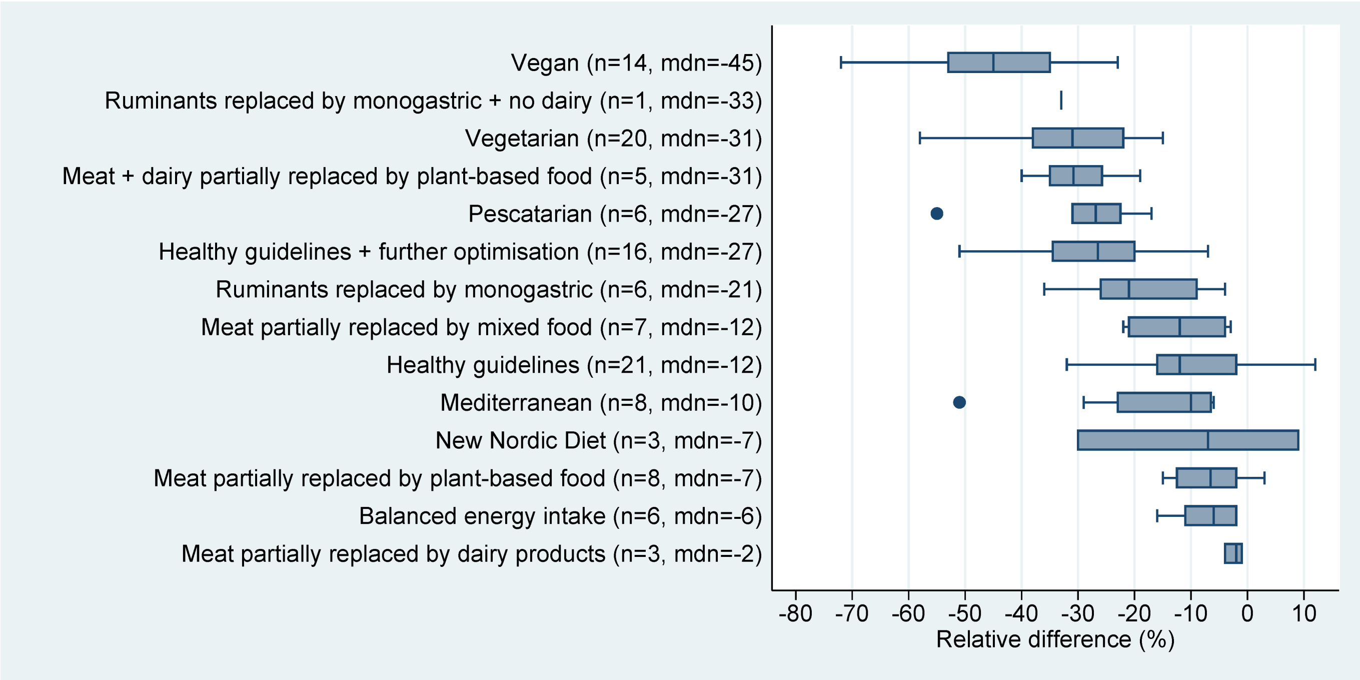


Figure 3: Relative differences in land use (m^2/capita/year) between current average diets and sustainable dietary patterns.

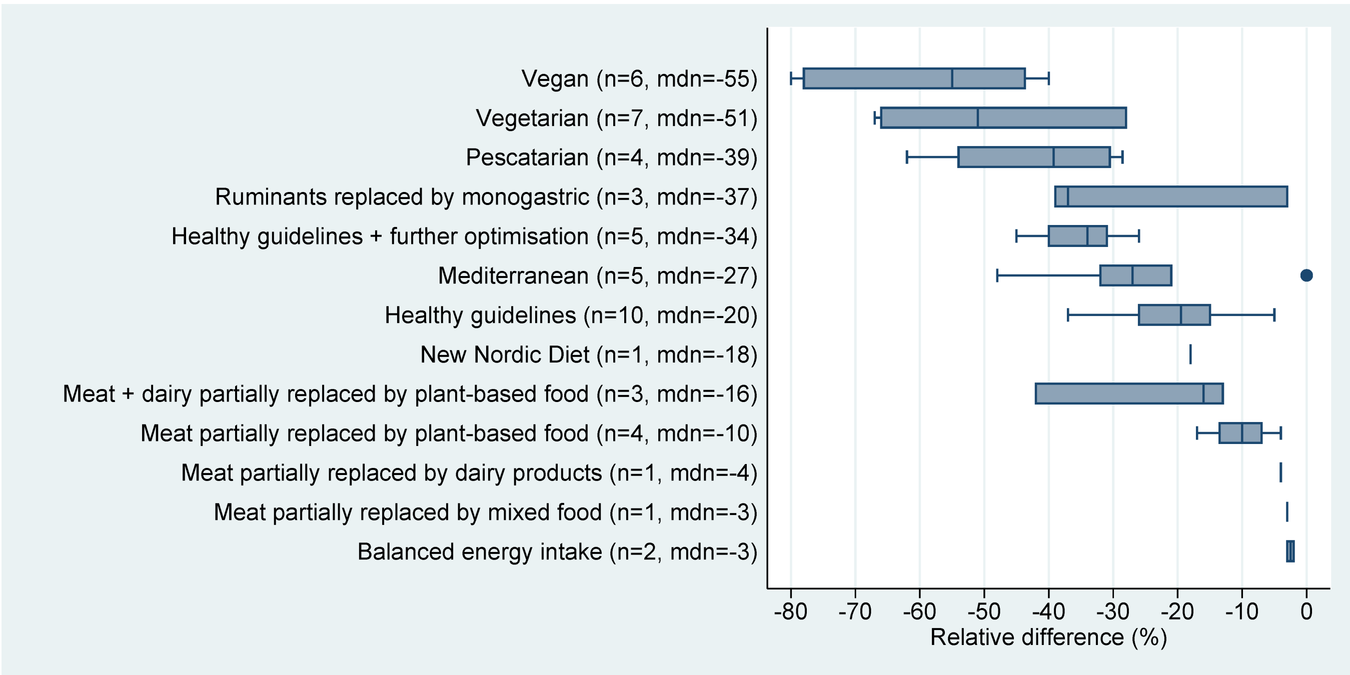
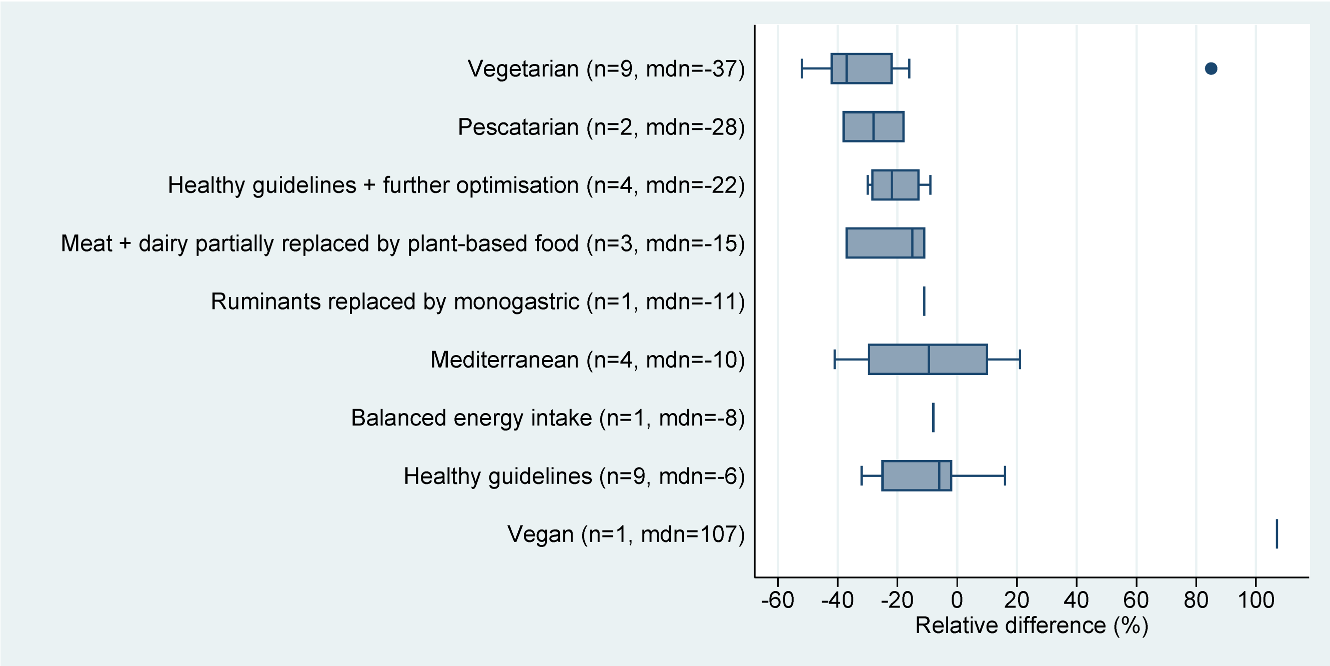


Figure 4: Relative differences in water use (L/capita/day) between current average diets and sustainable dietary patterns.



Note: n=number of studies, mdn=median. The lower and upper bounds of the boxes represent the 1st and 3rd quartiles, respectively, and the line within is the median. Whiskers show the minimum and maximum range, excluding outliers, which are shown as dots, and represent values more than 1.5 times the 1st and 3rd quartiles.

We assessed the sensitivity of our findings to study quality. Excluding papers that did not meet the three quality criteria resulted in minor differences in findings. The overall direction of impact did not change (sign test: p=0·5), and the ranking of sustainable diet types had strong correlation with the full list of studies for GHG emissions and land use (Spearman's rho: 0·93, p<0·0001; 0·83, p=0·003, respectively). The correlation between rankings was not significant for water use (Spearman's rho: 0·20, p=0·8); this was likely due to the number of scenarios decreasing from 34 to 4 when removing lower-quality studies (Supplementary table 2). The magnitude of environmental impacts for diets stayed similar (Supplementary figures 1a-c). Excluding grey literature sources had little effect, with the overall ranking of sustainable dietary patterns showing almost no change across the environmental indicators (sign test: p=0.21; Spearman's rho: 0·96-1·0, p<0·0001), (Supplementary table 2, Supplementary figures 2a-c).

Analyses of the health effects of sustainable diets were limited. Within the seven studies reporting health effects of adopting sustainable diets, 11 out of the 14 sustainable diet types were modelled, with a single estimate of all-cause health impacts for all but two of the 11 diet types. Most studies assessed the reduction in mortality risk from adopting a sustainable diet, either by all-cause or cause-specific mortality (Table 2). All studies showed positive health effects, ranging from <1% reduction in estimated mortality risk for vegetarian diets, to 19% for vegan diets, though some of these were not statistically significant. The magnitude of health effects across the sustainable dietary patterns did not show a statistical association with that of environmental benefit.

Table 2: Health effects of sustainable dietary patterns.

Study	Country	Sustainable diet type	Health indicator	Change in health outcome (95%CI)*
Sabate 2015	US/Canada	Vegan	All-cause mortality rate	19.2%
Soret 2014 [47]	US/Canada	Vegetarian	All-cause mortality risk	9% (0-17)
Tilman 2014 [6]	Globally	Vegetarian	All-cause mortality risk	<1% (0-2)**
Sabate 2015	US	Vegetarian	All-cause mortality rate	15.9%
Aston 2012 [19]	UK	Meat partially replaced by mixed food	CHD risk (men)	9.7% (-3.5-22)
Aston 2012 [19]	UK	Meat partially replaced by mixed food	CHD risk (women)	6.4% (-1.8-14.3)
Aston 2012 [19]	UK	Meat partially replaced by mixed food	Diabetes mellitus risk (men)	12% (-4.5-22.7)
Aston 2012 [19]	UK	Meat partially replaced by mixed food	Diabetes mellitus risk (women)	7.5% (0.5-14.5)
Aston 2012 [19]	UK	Meat partially replaced by mixed food	Colorectal cancer risk (men)	12.2% (6.4-18.0)
Aston 2012 [19]	UK	Meat partially replaced by mixed food	Colorectal cancer risk (women)	7.7% (4.0-11.3)
Soret 2014 [47]	US/Canada	Meat partially replaced by mixed food	All-cause mortality risk	14% (4-23)
Sabate 2015	US/Canada	Meat partially replaced by mixed food	All-cause mortality rate	7.2%
Biesbroek 2014 [23]	Netherlands	Meat partially replaced by plant-based food	All-cause mortality risk	10% (3-16)
Biesbroek 2014 [23]	Netherlands	Meat partially replaced by dairy	All-cause mortality risk	6% (-4-14)
Tilman 2014 [6]	Globally	Mediterranean	All-cause mortality risk	18% (17-19)
Sabate 2015	US/Canada	Pescatarian	All-cause mortality rate	17.6%
Milner 2015 [60]	UK	Healthy guidelines	Years of life lost^{+}	6%
Milner 2015 [60]	UK	Healthy guidelines + further optimisation	Years of life lost^{+}	7%
Scarborough 2012 [61]	UK	Meat, dairy partially replaced by plant-based food	Deaths averted	6%
Scarborough 2012 [61]	UK	Ruminants replaced by monogastric	Deaths averted	<1%

*Percentages refer to reductions for all health indicators, except for deaths averted

**Mortality risk reduction by cause: cancer 10%, coronary heart disease 20%, type 2 diabetes 42%

$^{+}$Years of life lost, at year 30 (after adoption of the sustainable diet scenario)

Discussion

Our review showed that reductions above 70% of GHG emissions and land use, and 50% of water use, could be achieved by shifting typical Western diets to more environmentally sustainable dietary patterns. Medians of these impacts across all studies suggest possible reductions of between 20-30%. This review is the most recent and comprehensive to date, and the first to compare impacts across GHG emissions, land use, and water use. This work supports the conclusions of previous reviews in this area[14, 15] which also pointed to the potential for reductions in GHG emissions and land use from dietary change. However, our review substantially expands the number of studies and dietary patterns assessed, and includes grey literature. Our use of multiple environmental indicators also highlights possible trade-offs across the proposed dietary patterns, both in magnitude and direction of the environmental impacts.

Underlying environmental data in the studies (where shown) on the land use, GHG emissions, and water use impacts from the production of food items showed decreasing impacts, from greatest to least, across ruminant meat, other meat, dairy, and plant-based foods [9, 23, 24, 32, 39, 46, 51, 60, 78]. Therefore, the large majority of scenarios showed decreased environmental footprints from replacement of plant- with animal-based foods. However, we note some exceptions. Eleven scenarios out of 210 showed higher environmental impacts of shifts to sustainable diets [32, 38, 55, 60, 62, 63, 73], with two scenarios having no effect [60, 63]. In some studies, the underlying data on environmental footprints for plant-based foods were similar to or higher than for some meats (e.g. water use per calorie of nuts, fruits and vegetables being higher than several animal-based foods [38, 62]). Therefore, replacing calories from meat reduction scenarios with increased plant-based foods produced higher water footprints or GHG emissions in some cases [38, 55, 60, 62, 73]. A more thorough review of GHG impacts across food items by Tilman and Clark confirms these overall trends and possible exceptions [8], though comparisons of impacts between any specific food items are likely to vary by region and food production context. The make-up of the alternative dietary patterns was also a factor in instances of higher environmental impacts. For example, in studies assessing shifts to US dietary guidelines [33, 62], increases in footprints appeared to be driven in part by the particular US recommendations to greatly increase dairy intake. In Vieux et al., meat reduction supplemented isocalorically by fruit and vegetables showed an increase in emissions, while a secondary scenario (and arguably more realistic) of replacement with mixed foods (grains, vegetables, and dairy) saw a net decrease [60]. Such scenarios highlight some of the complexity involved in assessing environmental sustainability of diets, and the context- and region-specific nature of such assessments.

Studies modelling the health impacts of shifts from typical Western diets to sustainable dietary patterns showed modest health gains from reductions in mortality rates and risks [8, 21, 25, 50, 79, 80]. There was no statistical association between the magnitude of environmental and health benefits, though the number of studies modelling health scenarios was limited. A recent review of health impacts of low-carbon diets confirms our findings [81]. The health benefits of sustainable diets may derive from increases in fruit and vegetable consumption and reductions in red and processed meat [6], as well as lower overall calorie intake for those individuals at risk of over-nutrition. However, health and environmental priorities may not always converge, for example, as sugar may have low environmental impacts per calorie relative to other foods, and some fruit or vegetables may have higher GHG emissions per calorie than dairy and non-ruminant meats [39, 46, 60, 78]. Intake of fish, the consumption of which is still below recommended levels in many regions, will also have to be reconciled with the fragility of many global wild-catch fisheries and unsustainable practices in aquaculture [82].

This review had several limitations. The available studies were from a narrow range of HICs with different baseline dietary patterns, and used largely HIC-specific environmental data sources. The results may therefore only be generalizable to HICs. The data on environmental impacts did not provide measures of variance, and we were limited to graphical and non-parametric statistical methods to assess the differences between sustainable dietary patterns. We were also unable to rule out any effects of publication bias in the literature. The use of environmental indicators varied across studies, such as whether blue, green or grey water (or a combination) was used, and whether GHG emissions included the often significant emissions from land use change. Our use of relative differences in the analysis helped to accommodate some of the differences in methodology across studies, and despite this heterogeneity, our resulting median impacts produced internally consistent and plausible trends; for example, vegan diets having greater reductions in GHG emissions than vegetarian; greater benefits from reducing meat and dairy consumption compared to meat alone; and replacing meat with dairy having little benefit.

There is an increasing body of evidence on which to base the integration of environmental priorities into dietary recommendations. Several of these dietary patterns are already promoted through public health efforts, such as the healthy dietary guidelines, the Mediterranean diet [83, 84], and the New Nordic Diet [85]. Brazil and Sweden have also recently made efforts to add environmental priorities into dietary guidelines [86, 87]. Additionally, our literature search retrieved studies measuring environmental impacts of potential dietary shifts resulting from carbon taxes on food products [88-91]. These studies calculated reductions in GHG emissions on average of about 6-9%, supporting our conclusions that dietary change can reduce environmental impacts, and offering a policy route for achieving these aims.

Several considerations regarding environmentally sustainable eating are worth noting. Firstly, the production of food (i.e. the growing of crops and raising of livestock) is the primary driver of environmental impacts, as opposed to later stages such as transport and processing [92, 93]. While local and seasonal diets have advantages such as protecting local economies and crop diversity, efforts to reduce dietary-related environmental impacts should focus on reducing animal-based foods in high-consuming societies.

However, complete removal of animal-source foods is not realistic in many cultures and may have important health implications. Meat and dairy are high-quality sources of protein and micronutrients, and ensuring adequate bioavailable supply of these is essential for public health [94]. This review has largely focused on population-level intake, and further work should consider dietary requirements of sub-population groups, including children and women of child-bearing age. Moderate consumption of pork and poultry may be consistent with a more sustainable diet, as these have lower environmental impacts than ruminant meat. Additionally, raising of livestock in some regions allows humans to derive nutritional benefit from non-arable land, or to utilize crop residues and food waste [95].

Lastly, shifts to sustainable diets must be affordable and desirable for consumers. Studies have shown that large reductions in GHG emissions are possible without complete exclusion of animal products [9], and studies using self-selected sustainable diets imply these could be culturally appropriate for at least some individuals [24, 27, 49, 50, 96]. However, extending these patterns to the majority of the population will require large efforts. In HICs, healthy foods are often more expensive than unhealthy ones [97], and rebalancing these relative prices will be critical to help steer consumers towards more-sustainable choices [98].

Our estimates would benefit greatly from more comprehensive data, and further work should generate regional and food-specific environmental impacts, including for fisheries and aquaculture, as well as measures of variance. A limited number of studies calculated a reduction in nitrogen and phosphorus water contamination from sustainable eating patterns [10, 52], and further studies on these and other indicators are required. The resilience of sustainable diets to future environmental changes, such as rainfall patterns and the effect of rising carbon dioxide on nutritional quality of food, needs to be assessed [99]. Little is also known about the environmental impacts of different dietary patterns in low- and middle-income countries. The reviewed diets cannot be designated sustainable in an absolute sense, as this will depend on population growth, evidence about planetary boundaries, and assumptions about other environmental trends [2], and more work is necessary to define sustainable diets along a more comprehensive range of environmental, economic and social indicators.

The impacts of sustainable diets are linked to a number of SDGs, including goals on sustainable agricultural practices, health, water use, and climate change. Promotion and uptake of these diets could therefore offer a route, along with other strategies, to achieving several of the SDGs.

Across a large and heterogeneous set of studies, several policy implications are clear: environmental benefits are possible in HICs from shifting current diets to a variety of more sustainable dietary patterns; environmental benefits are largely proportional to the magnitude of meat (particularly from ruminants) and dairy reduction; and a redoubling of efforts to promote the uptake of diets that support these changes could bring environmental and health benefits.

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LA, RG and AH designed the study protocol. LA analysed the data and drafted the paper. LA and EJ reviewed the literature. All authors were involved in data interpretation, critical revisions of the paper, and approved the final version.

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Supplementary material

Supplementary table 1A: Included studies, study details, and environmental impacts for GHG emissions.

Study	Sustainable diet type	Country	Year of baseline intake	Intake data type	Environmental data type	Includes emissions from land use change*	Isocaloric	% of meat or dairy reduction	Relative difference (%)
Abeliotis et al. (2016) [64]	Vegetarian	Greece	2011	FBS	LCA	N/A	Yes	-	-34
Abeliotis et al. (2016) [64]	Ruminants replaced by monogastric	Greece	2011	FBS	LCA	N/A	Yes	-	-24
Almendros et al. (2013) [19]	Mediterannean	Spain	2006	Dietary survey	LCA	Yes	No	-	-51
Aston et al. (2012) [21]	Meat partially replaced by mixed food	UK	2000-2001	Dietary survey	LCA	N/A	Yes	42%	-12
Audsley et al. (2009) [22]	Vegetarian	UK	2005	FBS	LCA	Yes	Yes	-	-40
Audsley et al. (2009) [22]	Ruminants replaced by monogastric	UK	2005	FBS	LCA	Yes	Yes	-	-36
Audsley et al. (2009) [22]	Meat + dairy partially replaced by plants-based food	UK	2005	FBS	LCA	Yes	Yes	50%	-35
Audsley et al. (2009) [22]	Meat + dairy partially replaced by plants-based food	UK	2005	FBS	LCA	Yes	Yes	50%	-40
Audsley et al. (2010) [23]	Ruminants replaced by monogastric	UK	2005	FBS	LCA	Yes	Yes	75% of ruminant replaced by 45% increase in monogastric	-9

Audsley et al. (2010)	23	Meat + dairy partially replaced by plants-based food	UK	2005	FBS	LCA	Yes	Yes	40% dairy, 64% meat	-19
Berners-Lee et al. (2012)	24	Vegan (meat replaced by plant-based foods)	UK	2008-2009	Combination of FBS and dietary survey	LCA	N/A	Yes	-	-31
Berners-Lee et al. (2012)	24	Vegetarian (meat replaced by dairy)	UK	2008-2009	Combination of FBS and dietary survey	LCA	N/A	Yes	-	-22
Berners-Lee et al. (2012)	24	Vegan (self-selected)	UK	2008-2009	Combination of FBS and dietary survey	LCA	N/A	Yes	-	-23
Berners-Lee et al. (2012)	24	Vegetarian (self-selected)	UK	2008-2009	Combination of FBS and dietary survey	LCA	N/A	Yes	-	-18
Berners-Lee et al. (2012)	24	Vegan (according to USDA)	UK	2008-2009	Combination of FBS and dietary survey	LCA	N/A	Yes	-	-25
Berners-Lee et al. (2012)	24	Vegetarian (according to USDA)	UK	2008-2009	Combination of FBS and dietary survey	LCA	N/A	Yes	-	-25
Biesbroek et al. (2014)	25	Meat partially replaced by plant-based food	Netherlands	1993-1997	Dietary survey	LCA	N/A	No	33%	-10
Biesbroek et al. (2014)	25	Meat partially replaced by dairy products	Netherlands	1993-1997	Dietary survey	LCA	N/A	No	33%	-1
Bryngelsson et al. (2016)	70	Vegan	Sweden	2013	Dietary survey	LCA	No	Yes	-	-72
Bryngelsson et al. (2016)	70	Vegetarian	Sweden	2013	Dietary survey	LCA	No	Yes	-	-36
Bryngelsson et al. (2016)	70	Ruminants replaced by monogastric	Sweden	2013	Dietary survey	LCA	No	Yes	-	-26

Bryngelsson et al. (2016)	70	Meat partially replaced by plant-based food	Sweden	2013	Dietary survey	LCA	No	Yes	50%	-15
Carbon Trust et al. (2016)	67	Healthy guidelines + further optimisation	UK	2008-2011	Dietary survey	LCA	N/A	Yes	-	-31
Davis et al. (2016)	73	Vegetarian	Global	2009	FBS	LCA	No	No	-	-56
Davis et al. (2016)	73	Mediterannean	Global	2009	FBS	LCA	No	No	-	-12
Davis et al. (2016)	73	Pescatarian	Global	2009	FBS	LCA	No	No	-	-55
Donati et al. (2016)	66	Healthy guidelines + further optimisation	Italy	2014	Dietary survey	LCA	N/A	No	-	-51
Fazeni and Steinmueller (2011)	28	Healthy guidelines	Austria	2001-2006	FBS	LCA	N/A	Yes	-	-32
Freyer and Weik (2008)	29	Healthy guidelines	Austria	2001	Dietary survey	LCA	N/A	No	-	-16
Germani et al. (2014)	30	Mediterannean	Italy	2005-2006	Dietary survey	Unclear	N/A	No	-	-29
Goldstein et al. (2016)	65	Vegan	Denmark	2003-2008	Dietary survey	LCA	No	Yes	-	-60
Goldstein et al. (2016)	65	Vegetarian	Denmark	2003-2008	Dietary survey	LCA	No	Yes	-	-46
Grabs (2015)	31	Vegetarian	Sweden	2006	Household expenditure survey	Input-output LCA/hybrid-LCA	N/A	Yes	-	-20
Green et al. (2015)	9	Healthy guidelines	UK	2008-2011	Dietary survey	LCA	No	Yes	-	-17
Green et al. (2015)	9	Healthy guidelines + further optimisation	UK	2008-2011	Dietary survey	LCA	No	Yes	-	-40
Heller and Keoleian (2014)	33	Healthy guidelines + further optimisation	US	2010	FBS	LCA	N/A	No	-	-33
Heller and Keoleian (2014)	32	Vegan	US	2010	FBS	LCA	N/A	No	-	-53

Heller and Keoleian (2014)	32	Vegetarian	US	2010	FBS	LCA	N/A	No	-	-33
Heller and Keoleian (2014)	32	Healthy guidelines	US	2010	FBS	LCA	N/A	No	-	-1
Heller and Keoleian (2014)	32	Healthy guidelines	US	2010	FBS	LCA	N/A	Yes	-	12
Hendrie et al. (2014)	34	Healthy guidelines	Australia	1995	Dietary survey	Input-output analysis	N/A	Yes	-	-23
Hendrie et al. (2014)	34	Healthy guidelines + further optimisation	Australia	1995	Dietary survey	Input-output analysis	N/A	No	-	-25
Hoolohan et al. (2013)	36	Vegetarian	UK	2008-2009	Combination of FBS and dietary survey	LCA	N/A	Yes	-	-35
Hoolohan et al. (2013)	36	Ruminants replaced by monogastric	UK	2008-2009	Combination of FBS and dietary survey	LCA	N/A	Yes	-	-18
Horgan et al. (2016)	72	Healthy guidelines	UK	2008-2011	Dietary survey	LCA	N/A	Yes	-	-15
Horgan et al. (2016)	72	Healthy guidelines + further optimisation	UK	2008-2011	Dietary survey	LCA	N/A	Yes	-	-27
Macdiarmid et al. (2012)	11	Healthy guidelines + further optimisation	UK	2008-2010	Dietary survey	LCA	N/A	Yes	-	-36
Martin et al. (2016)	68	Meat partially replaced by plant-based food	Sweden	2011	FBS	LCA	N/A	Yes	25%	-8
Martin et al. (2016)	68	Pescatarian	Sweden	2011	FBS	LCA	N/A	Yes	-	-31
Martin et al. (2016)	68	Healthy guidelines	Sweden	2011	FBS	LCA	N/A	No	-	-15
Meier and Christen (2013)	38	Vegan	Germany	2006	Dietary survey	Input-output LCA/hybrid-LCA	Yes	Yes	-	-53

Meier and Christen (2013)	[38]	Vegetarian	Germany	2006	Dietary survey	Input-output LCA/hybrid-LCA	Yes	Yes	-	-24
Meier and Christen (2013)	[38]	Healthy guidelines	Germany	2006	Dietary survey	Input-output LCA/hybrid-LCA	Yes	Yes	-	-11
Meier and Christen (2013)	[38]	Healthy guidelines + further optimisation	Germany	2006	Dietary survey	Input-output LCA/hybrid-LCA	Yes	Yes	-	-12
Noleppa (2012)	[40]	Healthy guidelines	Germany	2009	Combination of FBS and dietary survey	LCA	Yes	No	-	-14
Pairotti et al. (2014)	[42]	Vegetarian	Italy	-	"Italian Food Basket", official national metric of average intake	LCA	N/A	Yes	-	-15
Pairotti et al. (2014)	[42]	Healthy guidelines	Italy	-	"Italian Food Basket", official national metric of average intake	LCA	N/A	Yes	-	-2
Pairotti et al. (2014)	[42]	Mediterannean	Italy	-	"Italian Food Basket", official national metric of average intake	LCA	N/A	Yes	-	-7
Perignon et al. (2016)	[75]	Healthy guidelines + further optimisation	France	2006-2007	Dietary survey	Input-output LCA/hybrid-LCA	No	Yes	-	-30
Ranganathan et al. (2016)	[69]	Meat partially replaced by mixed food	Global (those eating above min. kcals)	2006	FBS	Environmental impacts model	Yes	Yes	50%	-4.2

Ranganathan et al. (2016)	69	Balanced energy intake	Global (those eating above min. kcals)	2006	FBS	Environmental impacts model	Yes	Yes	50%	-2.8
Ranganathan et al. (2016)	69	Ruminants replaced by monogastric	Global (those eating above min. kcals)	2006	FBS	Environmental impacts model	Yes	Yes	33%	-3.5
Ranganathan et al. (2016)	69	Meat partially replaced by plant-based food	Global (those eating above min. kcals)	2006	FBS	Environmental impacts model	Yes	Yes	33%	-4.4
Ranganathan et al. (2016)	69	Balanced energy intake	Global (those eating above min. kcals)	2006	FBS	Environmental impacts model	Yes	Yes	33%	-1.8
Risku-Norja et al. (2009)	45	Vegan	Finland	2006	FBS	LCA	N/A	Yes	-	-48
Risku-Norja et al. (2009)	45	Healthy guidelines + further optimisation	Finland	2006	FBS	LCA	N/A	Yes	-	-16
Risku-Norja et al. (2009)	45	Ruminants replaced by monogastric + no dairy	Finland	2006	FBS	LCA	N/A	Yes	-	-33
Roos et al. (2015)	46	Healthy guidelines	Sweden	2010-2011	Dietary survey	LCA	Yes	Yes	-	-32
Sabate et al. (2015)	74	Vegan	US/Can	2001-2007	Dietary survey	LCA	N/A	Yes	N/A	-42
Sabate et al. (2015)	74	Vegetarian	US/Can	2001-2007	Dietary survey	LCA	N/A	Yes	N/A	-28

Sabate et al. (2015)	74	Meat partially replaced by mixed food	US/Can	2001-2007	Dietary survey	LCA	N/A	Yes	N/A	-20
Sabate et al. (2015)	74	Pescatarian	US/Can	2001-2007	Dietary survey	LCA	N/A	Yes	N/A	-24
Saxe (2014)	47	New Nordic Diet	Denmark	2011	Combination of FBS and dietary survey	LCA	Yes	Yes	-	-30
Saxe et al. (2013)	48	Healthy guidelines	Denmark	2011	Combination of FBS and dietary survey	LCA	No	Yes	-	-8
Saxe et al. (2013)	48	New Nordic Diet	Denmark	2011	Combination of FBS and dietary survey	LCA	No	Yes	-	-7
Scarborough et al. (2014)	49	Vegan	UK	1993-1999	Dietary survey	LCA	N/A	Yes	-	-50
Scarborough et al. (2014)	49	Vegetarian	UK	1993-1999	Dietary survey	LCA	N/A	Yes	-	-35
Scarborough et al. (2014)	49	Meat partially replaced by mixed food	UK	1993-1999	Dietary survey	LCA	N/A	Yes	Compares meat intakes of <50g/d vs. >100g/d	-21
Soret et al. (2014)	50	Vegetarian	US/Can	2001-2007	Dietary survey	LCA	N/A	Yes	-	-29
Soret et al. (2014)	50	Meat partially replaced by mixed food	US/Can	2001-2007	Dietary survey	LCA	N/A	Yes	80%	-22
Springmann et al. (2016)	71	Vegan	Global	2005-2007	FBS	LCA	No	No	-	-67
Springmann et al. (2016)	71	Vegetarian	Global	2005-2007	FBS	LCA	No	No	-	-58
Springmann et al. (2016)	71	Healthy guidelines	Global	2005-2007	FBS	LCA	No	No	-	-24
Stamm (2015)	61	Vegan	Norway	2010-2011	Dietary survey	LCA	N/A	Yes	-	-39

Stamm (2015)	[61]	Vegetarian	Norway	2010-2011	Dietary survey	LCA	N/A	Yes	-	-17
Stamm (2015)	[61]	Meat partially replaced by plant-based food	Norway	2010-2011	Dietary survey	LCA	N/A	Yes	60%	-15
Stamm (2015)	[61]	Balanced energy intake	Norway	2010-2011	Dietary survey	LCA	N/A	Yes	-	-16
Stamm (2015)	[61]	Pescatarian	Norway	2010-2011	Dietary survey	LCA	N/A	Yes	-	-17
Thompson et al. (2013)	[53]	Healthy guidelines + further optimisation	France	2006-2007	Dietary survey	LCA	No	Yes	-	-25
Tilman and Clark (2014)	[8]	Vegetarian	Global	2009	FBS	LCA	No	No	-	-43
Tilman and Clark (2014)	[8]	Mediterannean	Global	2009	FBS	LCA	No	No	-	-6
Tilman and Clark (2014)	[8]	Pescatarian	Global	2009	FBS	LCA	No	No	-	-30
Tom et al. (2015)	[62]	Balanced energy intake	US	2010	FBS	LCA	N/A	Yes	-	-9
Tom et al. (2015)	[62]	Healthy guidelines	US	2010	FBS	LCA	N/A	Yes	-	11
Tom et al. (2015)	[62]	Healthy guidelines	US	2010	FBS	LCA	N/A	No	-	6
Trolle et al. (2014)	[54]	Healthy guidelines	Denmark	2003-2008	Dietary survey	LCA	N/A	Yes	-	-4
Trolle et al. (2014)	[54]	Healthy guidelines + further optimisation	Denmark	2003-2008	Dietary survey	LCA	N/A	Yes	-	-23
Tukker et al. (2011)	[55]	Healthy guidelines	EU	2003	FBS	Input-output analysis	No	Yes	-	2
Tukker et al. (2011)	[55]	Mediterannean	EU	2003	FBS	Input-output analysis	No	Yes	-	-6
Tukker et al. (2011)	[55]	Healthy guidelines + further optimisation	EU	2003	FBS	Input-output analysis	No	Yes	-	-7
Tyszler et al. (2016)	[56]	Vegan	Netherlands	2007-2010	Dietary survey	LCA	N/A	Yes	-	-40

Tyszler et al. (2016)	56	Pescatarian	Netherlands	2007-2010	Dietary survey	LCA	N/A	Yes	-	-23
Tyszler et al. (2016)	56	Healthy guidelines	Netherlands	2007-2010	Dietary survey	LCA	N/A	Yes	-	-10
Tyszler et al. (2016)	56	Healthy guidelines + further optimisation	Netherlands	2007-2010	Dietary survey	LCA	N/A	Yes	-	-38
Van Dooren et al. (2014)	57	Vegan	Netherlands	1998	Dietary survey	LCA	N/A	Yes	-	-35
Van Dooren et al. (2014)	57	Vegetarian	Netherlands	1998	Dietary survey	LCA	N/A	Yes	-	-22
Van Dooren et al. (2014)	57	Healthy guidelines + further optimisation	Netherlands	1998	Dietary survey	LCA	N/A	Yes		-17
Van Dooren et al. (2014)	57	Healthy guidelines	Netherlands	1998	Dietary survey	LCA	N/A	Yes	-	-12
Van Dooren et al. (2014)	57	Mediterannean	Netherlands	1998	Dietary survey	LCA	N/A	Yes	-	-17
Van Dooren et al. (2016)	63	New Nordic Diet	Netherlands	2007-2010	Dietary survey	LCA	N/A	Yes	-	9
Van Dooren et al. (2016)	63	Healthy guidelines	Netherlands	2007-2010	Dietary survey	LCA	N/A	No	-	-13
Van Dooren et al. (2016)	63	Mediterannean	Netherlands	2007-2010	Dietary survey	LCA	N/A	No	-	-8
Van Dooren et al. (2016)	63	Healthy guidelines + further optimisation	Netherlands	2007-2010	Dietary survey	LCA	N/A	No	-	-26
Vieux et al. (2012)	60	Meat partially replaced by plant-based food	France	2006-2007	Dietary survey	LCA	N/A	Yes	20%; 50g/day min.	0
Vieux et al. (2012)	60	Meat partially replaced by dairy products	France	2006-2007	Dietary survey	LCA	N/A	Yes	20%; 50g/day min.	-2
Vieux et al. (2012)	60	Meat partially replaced by mixed food	France	2006-2007	Dietary survey	LCA	N/A	Yes	20%; 50g/day min.	-3

Vieux et al. (2012)	60	Balanced energy intake (assuming low physical activity)	France	2006-2007	Dietary survey	LCA	N/A	Yes	-	-11
Vieux et al. (2012)	60	Meat partially replaced by plant-based food	France	2006-2007	Dietary survey	LCA	N/A	Yes	65%; 50g/d max.	3
Vieux et al. (2012)	60	Meat partially replaced by dairy products	France	2006-2007	Dietary survey	LCA	N/A	Yes	65%; 50g/d max.	-4
Vieux et al. (2012)	60	Meat partially replaced by mixed food	France	2006-2007	Dietary survey	LCA	N/A	Yes	65%; 50g/d max.	-7
Vieux et al. (2012)	60	Balanced energy intake (assuming moderate physical activity)	France	2006-2007	Dietary survey	LCA	N/A	Yes	-	-2
Westhoek et al. (2014)	10	Meat partially replaced by mixed food	EU	2007	Combination of FBS and dietary survey	Environmental impacts model	Yes	Yes	50%	-5
Westhoek et al. (2014)	10	Meat (all meat) + dairy partially replaced by plants-based food	EU	2007	Combination of FBS and dietary survey	Environmental impacts model	Yes	Yes	50%	-31
Westhoek et al. (2014)	10	Meat (beef) + dairy partially replaced by plants-based food	EU	2007	Combination of FBS and dietary survey	Environmental impacts model	Yes	Yes	50%	-26

*N/A indicates not enough information was given in the study to assess if emissions included those from land use change

Supplementary table 1B: Included studies, study details, and environmental impacts for land use.

Study		Sustainable diet type	Country	Year of baseline intake	Intake data type	Environmental data type	Isocaloric	% of meat or dairy reduction	Relative difference (%)
Almendros et al. (2013)	19	Mediterannean	Spain	2006	Dietary survey	LCA	No	-	-32
Arnoult et al. (2010)	20	Healthy guidelines	UK & Wales	2003-4	Dietary survey	Environmental impacts model	Yes	-	-18
Audsley et al. (2010)	23	Ruminants replaced by monogastric	UK	2005	FBS	LCA	Yes	75% of ruminant replaced by 45% increase in monogastric	-39
Audsley et al. (2010)	23	Meat + dairy partially replaced by plants-based food	UK	2005	FBS	LCA	Yes	40% dairy, 64% meat	-42
Biesbroek et al. (2014)	25	Meat partially replaced by plant-based food	Netherlands	1993-1997	Dietary survey	LCA	No	33%	-10
Biesbroek et al. (2014)	25	Meat partially replaced by dairy products	Netherlands	1993-1997	Dietary survey	LCA	No	33%	-4
Bryngelsson et al. (2016)	70	Vegan	Sweden	2013	Dietary survey	LCA	Yes	-	-80
Bryngelsson et al. (2016)	70	Vegetarian	Sweden	2013	Dietary survey	LCA	Yes	-	-46
Bryngelsson et al. (2016)	70	Ruminants replaced by monogastric	Sweden	2013	Dietary survey	LCA	Yes	-	-37
Bryngelsson et al. (2016)	70	Meat partially replaced by plant-based food	Sweden	2013	Dietary survey	LCA	Yes	50%	-17
Carbon Trust et al. (2016)	67	Healthy guidelines + further optimisation	UK	2008-2011	Dietary survey	Own calculations	Yes	-	-34
Davis et al. (2016)	73	Vegetarian	Global	2009	FBS	Own calculations	No	-	-66
Davis et al. (2016)	73	Mediterannean	Global	2009	FBS	Own calculations	No	-	-21

Davis et al. (2016)	73	Pescatarian	Global	2009	FBS	Own calculations	No	-	-62
Donati et al. (2016)	66	Healthy guidelines + further optimisation	Italy	2014	Dietary survey	LCA	No	-	-26
Goldstein et al. (2016)	65	Vegan	Denmark	2003-2008	Dietary survey	LCA	Yes	-	-78
Goldstein et al. (2016)	65	Vegetarian	Denmark	2003-2008	Dietary survey	LCA	Yes	-	-67
Martin et al. (2016)	68	Meat partially replaced by plant-based food	Sweden	2011	FBS	LCA	Yes	25%	-10
Martin et al. (2016)	68	Pescatarian	Sweden	2011	FBS	LCA	Yes	-	-46
Martin et al. (2016)	68	Healthy guidelines	Sweden	2011	FBS	LCA	No	-	-21
Meier et al. (2014)	39	Vegan	Germany	2006	Dietary survey	Input-output LCA/hybrid-LCA	Yes	-	-44
Meier et al. (2014)	39	Vegetarian	Germany	2006	Dietary survey	Input-output LCA/hybrid-LCA	Yes	-	-28
Meier et al. (2014)	39	Healthy guidelines	Germany	2006	Dietary survey	Input-output LCA/hybrid-LCA	Yes	-	-15
Meier et al. (2014)	39	Healthy guidelines + further optimisation	Germany	2006	Dietary survey	Input-output LCA/hybrid-LCA	Yes	-	-18
Noleppa and von Witzke (2012)	41	Healthy guidelines	Germany	2011	Combination of FBS and dietary survey	Unclear	No	-	-10
Peters et al. (2007)	43	Vegetarian	NY (US)	2000	FBS	Own calculations	Yes	-	-55
Ranganathan et al. (2016)	69	Meat partially replaced by mixed food	Global (those eating above min. kcals)	2006	FBS	Environmental impacts model	Yes	50%	-3
Ranganathan et al. (2016)	69	Balanced energy intake	Global (those eating above min. kcals)	2006	FBS	Environmental impacts model	Yes	50%	-3

Ranganathan et al. (2016)	69	Ruminants replaced by monogastric	Global (those eating above min. kcals)	2006	FBS	Environmental impacts model	Yes	33%	-3
Ranganathan et al. (2016)	69	Meat partially replaced by plant-based food	Global (those eating above min. kcals)	2006	FBS	Environmental impacts model	Yes	33%	-4
Ranganathan et al. (2016)	69	Balanced energy intake	Global (those eating above min. kcals)	2006	FBS	Environmental impacts model	Yes	33%	-2
Roos et al. (2015)	46	Healthy guidelines	Sweden	2010-2011	Dietary survey	LCA	Yes	-	-21
Temme et al. (2013)	51	Vegan	Netherlands	2003	Dietary survey	Own calculations	No	-	-51
Temme et al. (2013)	51	Meat + dairy partially replaced by plants-based food	Netherlands	2003	Dietary survey	Own calculations	No	30%	-16
Thaler et al. (2015)	52	Healthy guidelines	Austria	2001-2006	Combination of FBS and dietary survey	Own calculations	Yes	-	-28
Tilman and Clark (2014)	8	Vegetarian	Global	2009	FBS	Own calculations	No	-	-28
Tilman and Clark (2014)	8	Mediterannean	Global	2009	FBS	Own calculations	No	-	-27
Tilman and Clark (2014)	8	Pescatarian	Global	2009	FBS	Own calculations	No	-	-29
Tyszler et al. (2014)	56	Vegan	Netherlands	2007-2010	Dietary survey	LCA	Yes	-	-40
Tyszler et al. (2014)	56	Pescatarian	Netherlands	2007-2010	Dietary survey	LCA	Yes	-	-33
Tyszler et al. (2014)	56	Healthy guidelines	Netherlands	2007-2010	Dietary survey	LCA	Yes	-	-5
Tyszler et al. (2014)	56	Healthy guidelines + further optimisation	Netherlands	2007-2010	Dietary survey	LCA	Yes	-	-40
Van Dooren et al. (2014)	57	Vegan	Netherlands	1998	Dietary survey	LCA	Yes	-	-59

Van Dooren et al. (2014)	[57]	Vegetarian	Netherlands	1998	Dietary survey	LCA	Yes	-	-51
Van Dooren et al. (2014)	[57]	Healthy guidelines + further optimisation	Netherlands	1998	Dietary survey	LCA	Yes		-45
Van Dooren et al. (2014)	[57]	Healthy guidelines	Netherlands	1998	Dietary survey	LCA	Yes	-	-37
Van Dooren et al. (2014)	[57]	Mediterannean	Netherlands	1998	Dietary survey	LCA	Yes	-	-48
Van Dooren et al. (2016)	[63]	New Nordic Diet	Netherlands	2007-2010	Dietary survey	LCA	Yes	-	-18
Van Dooren et al. (2016)	[63]	Healthy guidelines	Netherlands	2007-2010	Dietary survey	LCA	No	-	-26
Van Dooren et al. (2016)	[63]	Mediterannean	Netherlands	2007-2010	Dietary survey	LCA	No	-	0
Van Dooren et al. (2016)	[63]	Healthy guidelines + further optimisation	Netherlands	2007-2010	Dietary survey	LCA	No	-	-31
Westhoek et al. (2014)	[10]	Meat + dairy partially replaced by plants-based food	EU	2007	Combination of FBS and dietary survey	Environmental impacts model	Yes	50%	-13

Supplementary table 1C: Included studies, study details, and environmental impacts for water use.

Study		Sustainable diet type	Country	Year of baseline intake	Intake data type	Environmental data type	Isocaloric	% of meat or dairy reduction	Relative difference (%)
Almendros et al. (2013)	[19]	Mediterannean	Spain	2006	Dietary survey	LCA	No	-	-1
Capone et al. (2013)	[26]	Mediterannean	Italy	2005-2006	Dietary survey	Secondary data	No	-	-41
Carbon Trust et al. (2016)	[67]	Healthy guidelines + further optimisation	UK	2008-2011	Dietary survey	Secondary data	Yes	-	-17

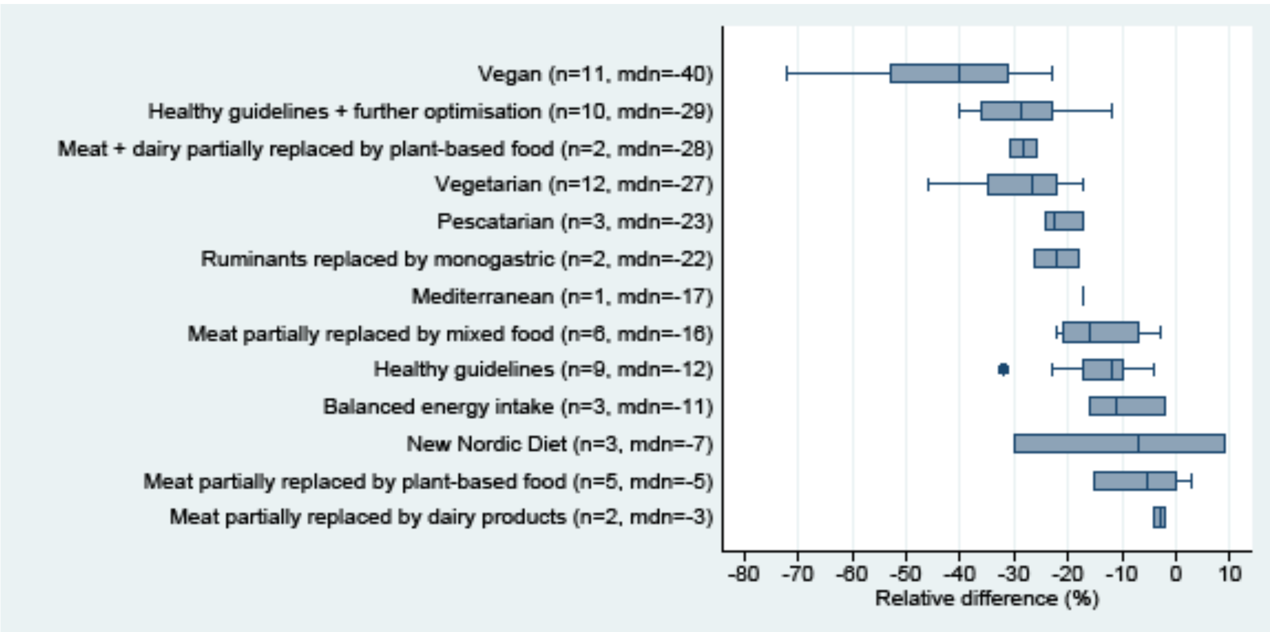
da Silva et al. (2013)	27	Vegetarian	Brazil (limited to one city)	2012	Dietary survey	Secondary data	No	-	-43
Davis et al. (2016)	73	Vegetarian	Global	2009	FBS	Secondary data	No	-	-22
Davis et al. (2016)	73	Mediterannean	Global	2009	FBS	Secondary data	No	-	21
Davis et al. (2016)	73	Pescatarian	Global	2009	FBS	Secondary data	No	-	-18
Donati et al. (2016)	66	Healthy guidelines + further optimisation	Italy	2014	Dietary survey	LCA	No	-	-9
Germani et al. (2014)	30	Mediterannean	Italy	2005-2006	Dietary survey	Unclear	No	-	-18
Hess et al. (2014)	35	Healthy guidelines	UK	2005	FBS	Secondary data	No	-	-3
Jalava et al. (2014)	37	Vegetarian	Global	2007-2009	FBS	Secondary data	Yes	-	-22
Jalava et al. (2014)	37	Healthy guidelines	Global	2007-2009	FBS	Secondary data	Yes	-	-2
Javala et al. (2016)	76	Vegetarian	Global	2009-2011	FBS	Secondary data	Yes	-	-16
Javala et al. (2016)	76	Healthy guidelines	Global	2009-2011	FBS	Secondary data	Yes	-	-6
Javala et al. (2016)	76	Meat + dairy partially replaced by plants-based food	Global	2009-2011	FBS	Secondary data	Yes	75%	-11
Meier and Christen (2013)	38	Vegan	Germany	2006	Dietary survey	Input-output LCA/hybrid-LCA	Yes	-	107
Meier and Christen (2013)	38	Vegetarian	Germany	2006	Dietary survey	Input-output LCA/hybrid-LCA	Yes	-	85
Meier and Christen (2013)	38	Healthy guidelines	Germany	2006	Dietary survey	Input-output LCA/hybrid-LCA	Yes	-	-26
Meier and Christen (2013)	38	Healthy guidelines + further optimisation	Germany	2006	Dietary survey	Input-output LCA/hybrid-LCA	Yes	-	-27
Renault and Wallender (2000)	44	Vegetarian	US	1995	FBS	Own calculations	Yes	-	-52

Renault and Wallender (2000)	44	Ruminants replaced by monogastric	US	1995	FBS	Own calculations	Yes	50% of beef replaced by poultry	-11
Renault and Wallender (2000)	44	Meat + dairy partially replaced by plants-based food	US	1995	FBS	Own calculations	Yes	25%	-15
Renault and Wallender (2000)	44	Meat + dairy partially replaced by plants-based food	US	1995	FBS	Own calculations	Yes	25%	-37
Tom et al. (2015)	62	Balanced energy intake	US	2010	FBS	Secondary data	Yes	-	-8
Tom et al. (2015)	62	Healthy guidelines	US	2010	FBS	Secondary data	Yes	-	16
Tom et al. (2015)	62	Healthy guidelines	US	2010	FBS	Secondary data	No	-	10
Vanham (2013)	58	Vegetarian	Austria	1996-2005	FBS	Secondary data	No	-	-37
Vanham (2013)	58	Healthy guidelines	Austria	1996-2005	FBS	Secondary data	No	-	-25
Vanham et al. (2013)	59	Vegetarian	EU	1996-2005	FBS	Secondary data	No	-	-38
Vanham et al. (2013)	59	Healthy guidelines	EU	1996-2005	FBS	Secondary data	No	-	-23
Vanham et al. (2013)	59	Healthy guidelines + further optimisation	EU	1996-2005	FBS	Secondary data	No	-	-30
Vanham et al. (2016)	77	Vegetarian	Netherlands	1996-2005	FBS	Secondary data	No	-	-42
Vanham et al. (2016)	77	Healthy guidelines	Netherlands	1996-2005	FBS	Secondary data	No	-	-32
Vanham et al. (2016)	77	Pescatarian	Netherlands	1996-2005	FBS	Secondary data	No	-	-38

Supplementary table 2: Number of sustainable diet types showing greater, lower, or neutral environmental impacts, and Spearman's coefficients, after removal of grey literature, and studies that did not meet quality criteria.

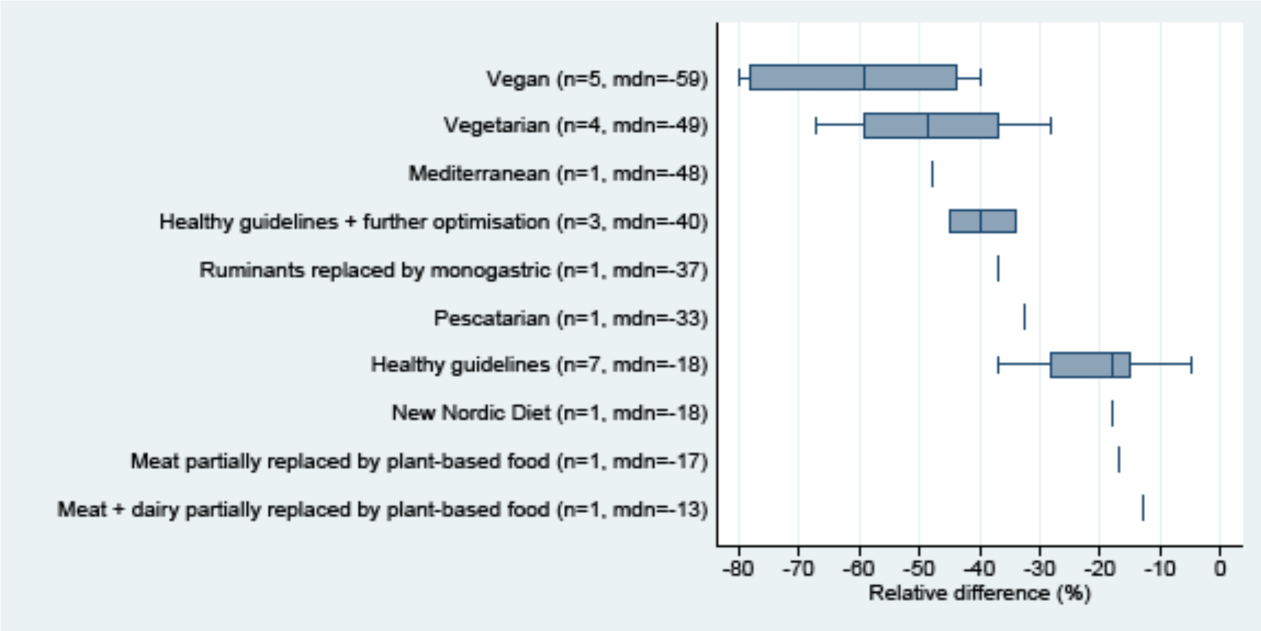
	GHG emissions		Land use		Water use	
	Quality	Grey literature	Quality	Grey literature	Quality	Grey literature
Greater	6	5	4	5	2	1
Lower	5	3	2	2	1	0
Neutral	2	6	4	4	1	8
Spearman's rho (ρ)	0.99, p<0.0001	0.97, p<0.0001	0.83, p=0.042	0.98, p<0.0001	0.4, p=0.6	1.0, p<0.0001

Supplementary figure 1A: Relative difference in GHG emissions (kg CO2eq/capita/year) between current average diets and sustainable dietary patterns, after excluding studies that did not meet quality criteria.



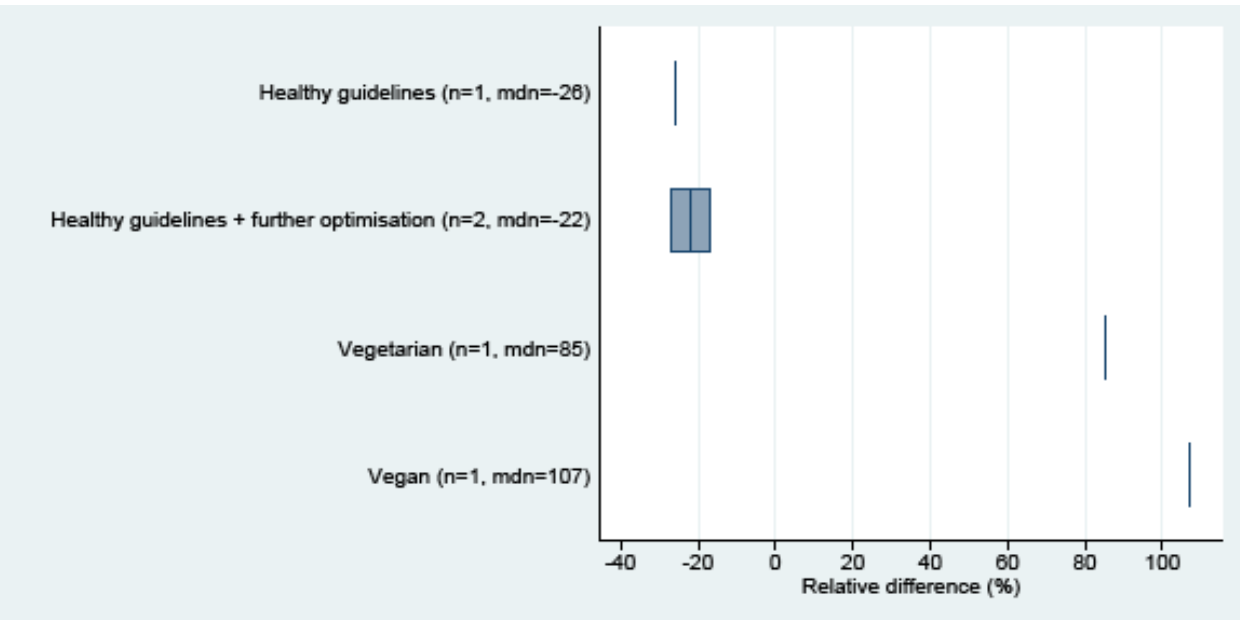
*n=number of studies; mdn=median

Supplementary figure 1B: Relative difference in land use (m2/capita/year) between current average diets and sustainable dietary patterns, after excluding studies that did not meet quality criteria.



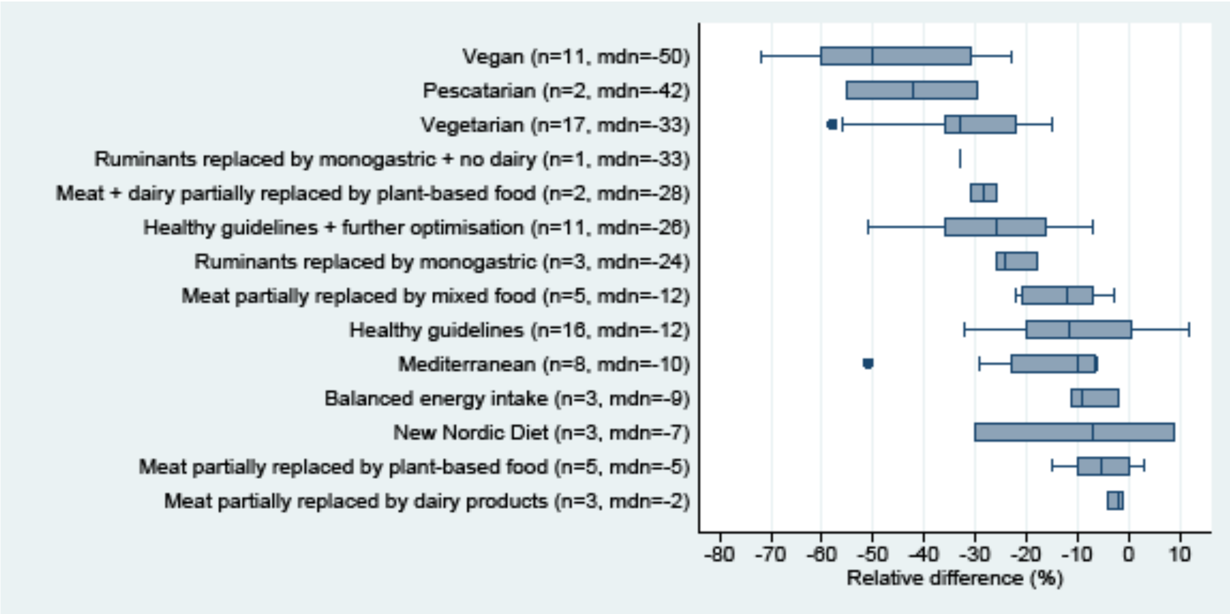
*n=number of studies; mdn=median

Supplementary figure 1C: Relative difference in water use (L/capita/day) between current average diets and sustainable dietary patterns, after excluding studies that did not meet quality criteria.



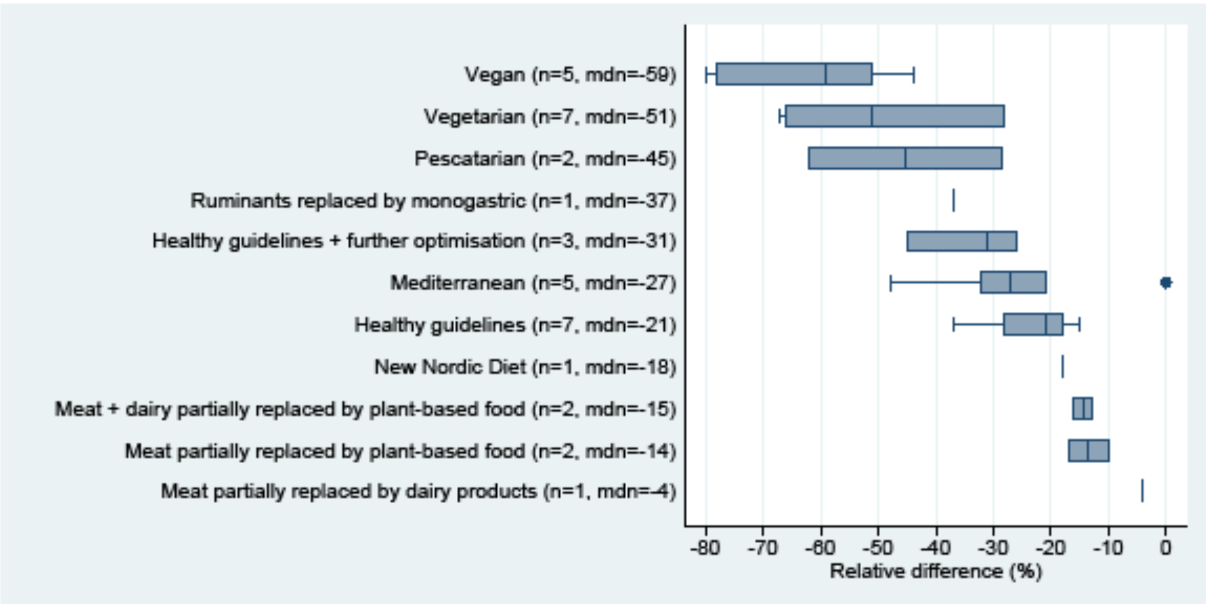
*n=number of studies; mdn=median

Supplementary figure 2A: Relative difference in GHG emissions (kg CO_2eq/capita/year) between current average diets and sustainable dietary patterns, after excluding grey literature.



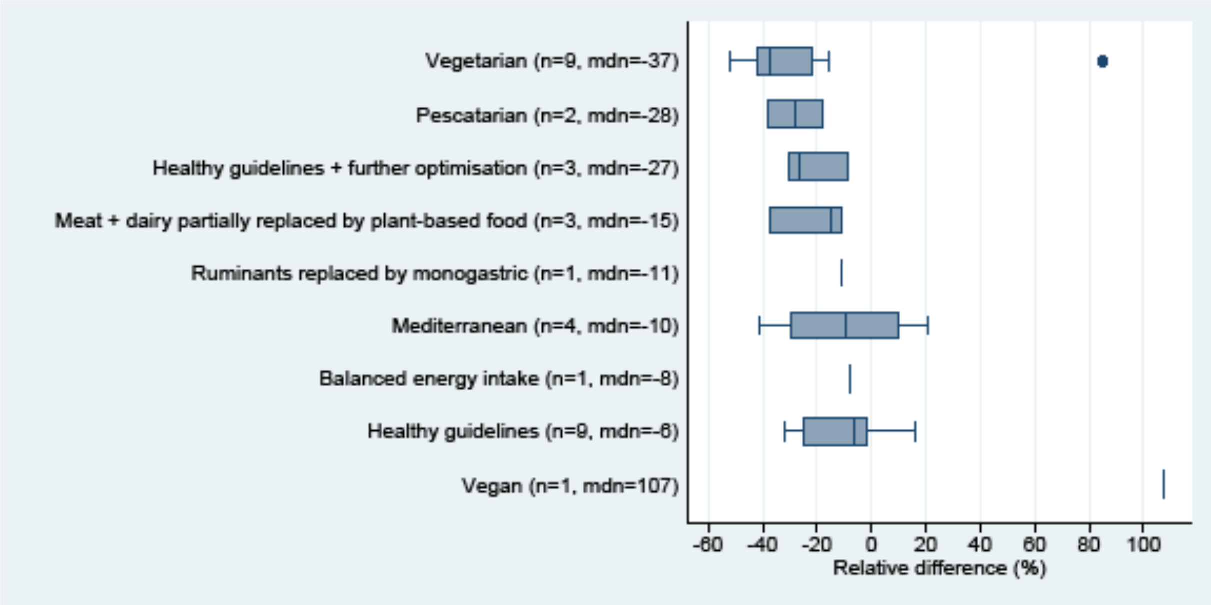
*n=number of studies; mdn=median

Supplementary figure 2B: Relative difference in land use (m^2/capita/year) between current average diets and sustainable dietary patterns, after excluding grey literature.



*n=number of studies; mdn=median

Supplementary figure 2C: Relative difference in water use (L/capita/day) between current average diets and sustainable dietary patterns, after excluding grey literature.



*n=number of studies; mdn=median

Supplementary file 1: Systematic review protocol (dated June 1st, 2015)

1) Research question
To review the diet-related environmental impacts of shifting food consumption from average current diets to sustainable alternative diets, for available countries.

2) Background
Agricultural systems globally exert large environmental impacts. Agriculture contributes to about 20% of global greenhouse gas emissions [1], 70% of water use, and occupies more than a third of all land [1,2]. Shifts to more sustainable diets may therefore have the potential to mitigate some of these impacts.
Many studies have calculated the environmental impacts of sustainable diets. However, there are still varying opinions on what a sustainble diet may specifically look like, as well as some criticism of the effectiveness of sustainable eating [3,4]. This has likely detracted from meaningful policy change, an example of which has been the recent opposition to the US Dietary Guidelines Advisory Committee's recommendation of including environmental considerations in dietary guidelines [5]. Several previous reviews have been conducted on sustainable diets, however, these have largely been general literature reviews commenting on the models or metrics [7,8], or have not incorporated all available evidence on the estimates of environmental impacts [6]. The current proposed analysis will be a systematic review to update all available evidence on environmental impacts of dietary shifts.

3) Aims
This systematic review will primarily answer two questions:
- what are the various definitions of sustainable diets proposed in the literature?
- what are the environmental impacts of these sustainable diets, measured in terms of greenhouse gas emissions, land use, and water use, compared to current diets?

4) Search strategy
The following search concepts will be used:
1. (meat OR "sustainable diet*" OR "diet* pattern*" OR "diet* choice*" OR “diet* change*” OR “diet* recommendation*” OR “diet* guideline*” OR “diet* scenario*” OR “ diet* type*” OR “Mediterranean diet*” OR "food choice*" OR "food consumption" OR "health* diet*" OR “health* eat*”) AND (greenhouse OR GHG OR ecological OR “environment* sustain*” OR "global warming" OR climate OR water OR land OR “land-use” OR "environment* impact*" OR footprint*)
2. (diet*) AND (greenhouse OR GHG OR ecological OR “environment* sustain*” OR "global warming" OR climate OR water OR land OR “land-use” OR "environment* impact*" OR footprint*)
3. ("sustainable diet*" OR "diet* pattern*" OR "diet* choice*" OR “diet* change*” OR “diet* recommendation*” OR “diet* guideline*” OR “diet* scenario*” OR “ diet* type*” OR “Mediterranean diet*” OR "food choice*" OR "food consumption" OR "health* diet*" OR “health* eat*”) AND (environment*)
4. AND NOT (biogas* OR bioenergy OR manure OR antioxidant* OR antibiotic* OR immune* OR cropping OR yield OR "E. coli" OR safety OR metabolic OR

management OR *parasite* OR *forestry OR “crop-livestock” OR mice OR broiler*)

The databases to be searched will include Scopus, PubMed, Web of Science, Science Direct, ProQuest, and Google Scholar. Peer-reviewed studies will be included, as well as appropriate grey literature such as dissertations, conference proceedings, and reports, which meet the inclusion criteria described below. Studies will be hand-searched for other relevant references.

Inclusion criteria

- Quantifying environmental indicators in the form of greenhouse gas emissions, land use, or water use, between average population-level dietary intake and alternative diets
- Using dietary surveys or food balance sheets to inform the population-level baseline diets
- Studies conducted between 2000-2015, and using consumption or intake data from 1995 onwards
- English language

Exclusion criteria

- Comparison of environmental impacts of food items or single meals rather than diets
- Any alternative diets targeting meat or dairy reduction which did not supplement this decrease with other foods
- Review articles will be excluded, as well as multiple publications of the same study (e.g., results being published in a journal as well as report). In any such cases, the peer-reviewed source will be used.

5) Study quality and risk of bias

Study quality will be assessed through a checklist [9] that includes the following components:

- Current, average diets for comparison are based on dietary intake surveys at a national or sub-national level rather than national food balance sheets
- Description and source of the environmental impact data used in the model
- Baseline and comparison sustainable diets are isocaloric

A sensitivity analysis will be performed with the exclusion of any studies not meeting the above components.

6) Data extraction

Titles and abstracts will be used to filter papers into potential and non-relevant groups. Full-text versions will be accessed for potential papers. Potential papers meeting all inclusion criteria above will be extracted for details on the following variables: study location, years, source of environmental impacts data, type of sustainable diet measured, environmental impacts, degree of change, if any, for the sustainable diet (e.g., amount of meat reduction), and energy content of baseline and alternative diets. Data will be stored in Excel. Half of the records will be screened and have data extracted independently by a second reviewer, to limit exclusion of relevant studies. Half of relevant studies will have also have data extraction checked to limit any errors.

7) Data analysis

Differences in environmental impacts between baseline and alternative diets will be compared, stratified by type of alternative diet. As standard errors are not available for the types of studies being reviewed, statistical tests will not be performed. Results will be displayed with box plots, using means and ranges to compare effects across types of sustainable diet.

8) Conclusions

This review will quantitatively assess the environmental impacts between current and alternative sustainable diets, for available countries. The results will provide a synthesis of possible iterations of sustainable diets, and their estimated environmental impacts, to help inform policy decisions around integrating environmental considerations into dietary guidelines.

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RESEARCH PAPER COVER SHEET

Please note that a cover sheet must be completed for each research paper included within a thesis.

SECTION A – Student Details

Student ID Number	231894	**Title**	Mr
First Name(s)	Lukasz		
Surname/Family Name	Aleksandrowicz		
Thesis Title	Impact of dietary shifts in India on greenhouse gas emissions, land use, water use, and food expenditure: a nationally-representative study		
Primary Supervisor	Prof Sir Andy Haines		

If the Research Paper has previously been published please complete Section B, if not please move to Section C.

SECTION B – Paper already published

Where was the work published?	British Journal of Nutrition		
When was the work published?	May 2017		
If the work was published prior to registration for your research degree, give a brief rationale for its inclusion			
Have you retained the copyright for the work?*	Yes	Was the work subject to academic peer review?	Yes

*If yes, please attach evidence of retention. If no, or if the work is being included in its published format, please attach evidence of permission from the copyright holder (publisher or other author) to include this work.

SECTION C – Prepared for publication, but not yet published

Where is the work intended to be published?	N/A
Please list the paper's authors in the intended authorship order:	N/A

Stage of publication	Choose an item.

SECTION D – Multi-authored work

For multi-authored work, give full details of your role in the research included in the paper and in the preparation of the paper. (Attach a further sheet if necessary)	I designed the study, cleaned the data, performed the analysis, drafted the manuscript, prepared and submitted the final version, and responded to peer reviewer comments.

SECTION E

Student Signature	[redacted]
Date	Apr. 2, 2019

Supervisor Signature	[redacted]
Date	2nd April 2019

Comparison of food consumption in Indian adults between national and sub-national dietary data sources

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Supplementary material: Figures (5)

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Abstract

Accurate data on dietary intake are important for public health, nutrition and agricultural policy. The National Sample Survey is widely used by policymakers in India to estimate nutritional outcomes in the country, but has not been compared with other dietary data sources. To assess relative differences across available Indian dietary data sources, we compare intake of food groups across six national and sub-national surveys between 2004 and 2012, representing various dietary intake estimation methodologies, including household consumer expenditure surveys (HCES), food frequency questionnaires (FFQ), food balance sheets (FBS), and 24-ho recall (24HR) surveys. We matched data for relevant years, regions, and economic groups, for ages 16-59. One set of national HCES and the 24HR showed a decline in food intake in India between 2004-2005 and 2011-2012, whereas another HCES and FBS showed an increase. Differences in intake were smallest between the two HCES (1% relative difference). Relative to these, FFQ and FBS had higher intake (13 and 35%), and the 24HR lower intake (-9%). Cereal consumption had high agreement across comparisons (average 5% difference), whereas fruit and nuts, eggs, meat and fish, and sugar had the least (120, 119, 56, and 50% average differences, respectively). Spearman coefficients showed high correlation of ranked food group intake across surveys. The underlying methods of the compared data highlight possible sources of under- or over-estimation, and influence their relevance for addressing various research questions and programmatic needs.

Introduction

Accurate data on dietary intake are important for several policy areas, including nutrition, agriculture, and public health. Three types of sources are generally used for estimating food consumption in populations: food balance sheets (FBS), household consumer expenditure surveys (HCES), and individual intake surveys[1,2]. The Food and Agriculture Organisation (FAO) calculates annual FBS for countries, which estimate national-level availability of major food commodities, as a function of production, imports, exports, and adjustments for waste. HCES are conducted on a frequent basis by national statistics offices, using nationally representative sampling frames, and collect data on household-level purchases of a comprehensive set of food commodities. Individual intake surveys come in a variety of designs, including food frequency questionnaires (FFQ), 24-hour recall (24HR) surveys, and weighed food records. These surveys are generally regarded as providing more accurate individual-level estimates of food consumption than FBS or HCES, though they are more difficult and expensive to conduct, and thus are more commonly used on specific study populations rather than at national levels[1]. The choice of data type used by researchers and policymakers often depends on availability.

Much nutritional research has focused on India, where historically high rates of undernutrition, as well as growing over-nutrition, impose heavy burdens on health and development[3-5]. Several data sources exist in the country on dietary intake, and they have been variously used to study and describe, for example, consumption of major food groups and associated changes over time[4,6-10], absolute micronutrient intake[11], and health outcomes related to nutritional intake[12,13], among others[14,15].

Specifically, the Indian government's National Sample Survey (NSS) HCES have been used to describe the country's dietary transition from the 1980s to 2000s[4,7]. It has been suggested that several stages of transition with varying characteristics have unfolded in the country[6,9], though on the whole, diets have seen a decline in cereals, and an increase in energy content from vegetable- and animal-source fats. Alongside changes in food consumption over these years, recent estimates show that in 2014, about 27% of Indian adults were overweight, whereas 39% of children under 5 were stunted[16]. Despite India's growing economy, reductions in undernutrition have been materialising slowly[17].

However, challenges remain in using Indian dietary data to explain nutritional trends and drivers. Overall trends in dietary intake across time are still not fully clear, partly due to a lack of reliable data[8]. The NSS has shown a steady and counterintuitive decrease in consumed energy content from 1980 to 2010 as incomes have grown, with a small rebound in caloric intake only in the last available data year of 2012[8,18]. Evidence suggests the recent decreasing energetic trends in these data may be a function of some underestimation in this survey, such as not fully accounting for increased consumption of food outside the home[19,20].

Measuring food consumption is generally a difficult exercise[21], and studies have shown that the choice of data methodology applied to a given population can affect the resulting intake estimates[20,22-25]. Intake data are therefore often compared against an alternative method for a given sample or population for the purposes of validation, or to determine relative differences between the compared methods[2,22-

26)[26]. Despite researchers' and policymakers' reliance on the NSS, it has not been compared with other sources of dietary data in the country.

We compare intake of major food groups using six national and sub-national sources of Indian food consumption, representing various dietary intake estimation methods, and assess the impact of these methods on relative differences in food consumption.

Methods

Data

National Sample Survey

The NSS is an annual, nationally representative HCES, representing a random sample of households across the country. The questionnaire records the quantity and value of approximately 250 food and beverage items purchased in the last 30 days, among other consumer goods[(18,27)]. We used rounds 61, 66, and 68 of the survey, conducted between July and June of 2004-2005, 2009-2010, and 2011-2012, respectively, to match the years of data collection as close as possible to our other compared data sources. We additionally compare the 2011-2012 data from an alternative NSS survey format (named "type 2") that was recently implemented and used 7-day recall for meats, eggs, oils, fruits, and vegetables (though it retained a 30-day recall for cereals, pulses, and sugar)[(27)].

India Health and Development Survey

The India Health and Development Survey (IHDS) was a nationally representative HCES, conducted over two waves in 2004-2005 and 2011-12. It recorded, among other socioeconomic and health indicators, the quantity and value of purchased food groups in the last 30 days, such as vegetables, meats, and legumes, as well as several commonly-consumed individual items, such as rice and wheat[28].

FAO food balance sheets

The FAO's FBS provide a picture of food availability at the national level, and approximate per capita food availability by dividing national estimates by the total population[1]. We retrieved data for the years 2004, 2005, 2011, and 2012 from the FAOSTAT database[29].

National Nutrition Monitoring Bureau rural surveys

The National Nutrition Monitoring Bureau (NNMB) conducts periodic surveys in ten Indian states, using multi-stage random sampling of households, and following the NSS sampling frame. The surveys recorded individual-level intake within households using one 24HR survey[30]. The raw data from these surveys were not available, though NNMB reports provide mean individual-level intake of food groups by age for rural areas. We used these reported data for adults aged 18 years and above, from the surveys conducted on rural populations during 2004-2005 and 2011-2012[31,32].

Indian Migration Study

The Indian Migration Study (IMS) was a health and nutrition study conducted in 2005-2007, which surveyed factory workers in the four urban centres of Hyderabad, Bangalore, Nagpur and Lucknow, and their siblings living in rural areas, the majority of whom resided within the same Indian state as the urban centre. The survey used a FFQ of 184 dishes and food items, and recorded the frequency of intake and number of servings of each item in the one-year period prior to the survey. The study also collected recipes for each of the FFQ items, separately for rural and urban areas of each study site[33].

Andhra Pradesh Child and Parent Study

The Andhra Pradesh Child and Parent Study (APCAPS) is a prospective birth cohort study of households in 29 peri-urban villages of Ranga Reddy district in the Indian state of Telangana (previously Andhra Pradesh) that earlier took part in a food supplementation trial involving pregnant women and their offspring (1987-90). It uses a FFQ of 98 dishes and food items, based on the IMS FFQ and further refined for use in the APCAPS study setting. Here we used the third follow-up wave, which included children and their parents, conducted between 2010 and 2012[34]. The first wave was excluded as it did not collect detailed data on intake, whereas the second wave had a smaller sample size consisting of only children.

All data sources accounted for seasonality by using aggregated annual data or conducting fieldwork throughout the year (NSS, IHDS, FBS, and NNMB), or by specifically recording the variation in intake by time of year (IMS and APCAPS). A summary of data sources, including sample sizes, is presented in Table 1.

Analysis

We compare intake of major food groups, in grams/person/day, between survey types, matching for relevant year of survey, regions, sex, and economic groups, where available. HCES were used as the reference comparison against other methodologies (though strictly to assess relative differences rather than as a source of validation) due to the larger number of HCES data sets and the ability to match across the years and regions of other survey types. Food groups compared were cereals, pulses, dairy products (including butter), vegetable oils, meat (including fish), eggs, fruits and nuts, and vegetables (including root vegetables). Beverages were excluded. Intake was calculated for adults aged 16-59 years, for men and women combined (NNMB data were only available for ages 18 years and over), though stratification by age was not possible for FAO data.

Household expenditure surveys were converted to individual intake using Indian dietary energy requirement adjustment factors based on age and sex(32), and we used household weights to scale up to the national level. In the NSS data we additionally adjusted for high-income households which provide food to poorer households in exchange for labour or services, based on a standard methodology recommended by the NSS(18). We converted intake of the IMS and APCAPS FFQ items into individual food intake using the recipe sheets generated for these surveys, and aggregated these foods into food groups. Intake of each food group in the IMS data was additionally adjusted based on the validation of the IMS against a series of three 24HR surveys(26). Data from the FAO and NNMB surveys were extracted from publicly-available reports, and aggregated into the relevant food groups. FAO data were averaged for the years 2004-2005, and 2011-2012, to match the corresponding NSS and IHDS survey rounds. The IMS (conducted during 2005-2007) and APCAPS (2010-2012) asked respondents to recall intake over the previous year, and we have therefore used the years of intake in these surveys as 2004-2006 and 2009-2011, respectively, and matched these data for comparison to the IHDS-1 conducted in 2004-2005, and the NSS 66 conducted in 2009-2010.

Comparisons using the IMS were additionally stratified by income groups, as the employed IMS respondents and their siblings may have represented a higher socioeconomic sample than the average Indian population. For this, we generated a common standard of living index (SLI) between the IHDS and IMS, based on the SLI methodology developed in the Indian National Family Health Survey[(35)]. The components of this index include ownership of various assets and utilities, and we compared intake between the surveys for SLI tertiles. APCAPS data were compared with NSS rural households in Ranga Reddy district. Although matching for the same specific APCAPS villages was not possible in the NSS, the mean SLI between the APCAPS sample and the district-level NSS sample was very similar.

Relative differences in total daily intake, and for individual food groups (both in grams/day), were calculated for each dietary intake method comparison. We were not able to assess the statistical significance of the comparisons, as FAO and NNMB data do not allow for standard error calculations, and the main underlying uncertainty for all the methods is likely to be a function of measurement error rather than sample size. Spearman coefficients assessed the similarity of ranked food group intake across comparisons.

Ethics committee approval for IMS was obtained from the All India Institute of Medical Sciences Ethics Committee, and for APCAPS from the National Institutes of Nutrition, Hyderabad, and Public Health Foundation of India, New Delhi. Ethics committee approval for this analysis was obtained from the London School of Hygiene and Tropical Medicine. Consent was sought from the factory managers for the Indian Migrant Study and from the community leaders in the villages for the APCAPS study.

Results

Individual intake of food groups was calculated for twelve Indian national and sub-national data sources, conducted between 2004 and 2012, representing four dietary intake estimation methods (Table 1).

National-level trends over time

Both the NSS and NNMB surveys showed a decline nationally in total intake of food, in grams/day, between 2004-2005 and 2011-2012, though the IHDS and the FAO FBS showed an overall increase over the same years (Figure 1). Changes in food group consumption between 2004-2012 were mostly consistent across the NSS, IHDS, and FAO data; nationally, sources showed an increase in intake of pulses, dairy products, fats, eggs (no change in IHDS data), meat and fish, and sugar, and a decrease in cereals (no change in the FAO data). Intake of fruits and vegetables showed a decrease in NSS, and an increase in IHDS and FAO data. The IHDS, NSS, and IMS recorded higher overall intake in grams/person/day in urban than rural areas, for all available survey rounds (Supplementary figures 3 and 4).

In 2012, the most recent year of data availability, intake (kg) in India was highest for cereals (about 30-45%, depending on the data source), whereas consumption of dairy products and vegetables was also high (about 20-25%). Eggs and meat constituted the lowest intakes (2% or less), and consumption of pulses, oil, and sugar were also low (about 3-5%) (Figure 1).

Overall differences across survey types

Relative differences in combined intake of all food groups across the individual data comparisons varied markedly, and ranged from 1% between the IHDS-1 and the corresponding NNMB 24HR survey, to 50% between the NSS round 68 and FAO FBS. The IHDS and NSS expenditure surveys were similar to each other, showing a relative difference in total intake of just 1%, averaged across the two rounds of the surveys. Compared with HCES, FFQ and FBS showed higher absolute intake (on average, by 13 and 35%, respectively), and the 24HR surveys lower intake (average of -9%) (Table 2).

Type 1 and 2 formats were compared for round 68 of the NSS data (2011-2012). The type 2 survey showed substantially higher intake for those foods surveyed with the 7-day recall (vegetable oils, eggs, meat and fish, vegetables, and fruit and nuts; with increases of 9, 66, 43, 48, and 63%, respectively). Intake for the remaining foods that retained the 30-day recall in type 2 (cereals, pulses, and sugar) showed minor relative differences of about 1% compared to the same 30-day recall of these foods in the type 1 survey (Supplementary figure 5).

Food group differences across survey types

Of all food groups, intake of cereals showed the smallest relative differences in grams/person/day across the survey comparisons, ranging from -1 to 9%, with an average difference of 5%. Fruit and nuts, eggs, meat and fish, and sugar had high average relative differences across the comparisons (120, 119, 56, and 50% average differences, respectively). Fruit and nuts in particular had the highest variability in differences between comparisons, ranging from a -36% difference between the NSS and IHDS HCES, to a 264% difference between the expenditure surveys and FBS (Table 3).

Spearman's correlation analysis of food group ranks (intake of a food group as the proportion of total intake (kg)) showed very high correlation across surveys (Spearman's ρ 0.8-1.0 across surveys, *P*=0.01 to *P*<0.0001).

Discussion

We present a comparison of several sources of Indian dietary data, representing a variety of intake estimation methods. This is, to our knowledge, the first such analysis. We found differences in estimates of overall and food group intake across these comparisons when matching sources for year, sex, and region, which may be partly due to methodological differences across the surveys.

Compared with the national consumer expenditure surveys, relative differences in total estimated intake in grams/person/day varied from 1 to 50% across the other data sources. The two national expenditure surveys were most similar to each other, whereas the FFQ and FBS showed higher intake, and the 24HR surveys lower intake, in relation to these. Cereal consumption had high agreement across survey types, whereas fruit and nuts, eggs, meat and fish, and sugar had the least.

Recent work has suggested that the Indian expenditure and 24HR surveys may to some degree underestimate food consumed out of home[(19)], and this could partly explain the lower consumption recorded in these sources relative to FFQ and FBS data. The NSS records the value and number of snacks and meals, respectively, eaten out of the home from a single respondent (and IHDS records only the value of meals). This is generally the female adult of the household who recalls other household members' intake[19], and may therefore not be aware of some foods eaten out of the home[20,36,37]. The NNMB 24HR surveys share a similar limitation, and to our knowledge, do not provide details on how the nutritional composition of recalled food is determined, or how food outside the home is accounted for. However, the NSS is the longest-running source of nationally representative data, and is frequently used to analyse consumption trends in India. Two factors may help improve estimates of dietary intake from these expenditure data. First is the use of the "type 2" data, in which the use of a shorter recall period may help improve accuracy[27,38], particularly for nutrient-rich food groups. We calculated a 13% higher total intake in grams per person per day across all foods, and NSS-own estimates show about 6-9% higher dietary energy intake in rounds 66 and 68, when compared to the typical "type 1" 30 day recall [18,27]. Secondly, our calculations showed about 7-8% of NSS households' food expenditure was spent on snacks and food prepared outside the home (data not shown), and methods are needed to estimate intake from these sources. The two most recent NSS rounds have improved the specificity of food types eaten out of home[18,27], and while the survey provides the average estimated caloric, fat and protein composition of these items, the data format still does not allow for direct intake estimates of food groups or key nutritional indicators such as sugar, salt, or micronutrients.

The decline in overall intake between 2004-2005 and 2011-2012 in the NSS and NNMB data was not seen in the FAO FBS or the IHDS expenditure surveys. The FAO captures all food available at the national level, and may better assess all available food regardless of where it was purchased or eaten, though as the IHDS shares similar methodology to the NSS expenditure survey, it is not clear why they diverged on the direction of overall intake.

FAO FBS data have been shown to generally overestimate per capita intakes(2,25,39), as they may not fully account for wastage along the value chain from production up to consumption(25). However, the FBS are a common source for assessing trends over time in food availability(2). Comparisons of FBSs to other data sources have found that despite the general overestimation, FBSs can underestimate intake of certain food groups(23,25). In our study, the FBSs overestimated all food groups relative to NSS and IHDS expenditure surveys.

FFQ have been shown to have variable performance compared with other reference methods, in terms of direction and magnitude, though generally provide accurate ranking of food group intake(24). FFQ characteristics such as the number of recall items and recall period affect their accuracy(24). The IMS FFQ was calibrated against a series of three 24HR surveys(26), which are often used as a reference standard. Our use of these adjustments lessened the differences between the IMS and expenditure survey considerably, as the original IMS data showed almost 50% higher total intake than the HCES. A similar validation was not undertaken for APCAPS, and this may explain why the difference in intake between APCAPS and the HCES is higher than that between the IMS and the HCES.

As each dietary data method was designed for select purposes, it is expected that the dietary intakes in our comparisons would differ. Consumption of nutrient-rich food groups, as well as of sugar, showed high degrees of variability between the various data sources. This observation agrees with other recommendations that the dietary assessment methods we have reviewed may not be appropriate for precise assessment of individual-level energy or micronutrient intake[40-42]. Instead, these data sources could be applicable for broader nutritional assessments, such as relative comparisons between population groups or identification of groups at nutritional risk, measures of dietary diversity, time trends, categorisation of dietary patterns, and selection of foods for biofortification[40,42,43]. For example, the FFQ used in the IMS and APCAPS data was designed to examine relative differences in food consumption, nutrition, and health across population groups, and has been reported to be valid for such purposes[26]. Our findings of high correlation in ranked food group intake across all compared data sources also support these recommendations. Analyses of dietary impacts on health require the use of data sources that contain information on potential socioeconomic confounders, such as the IMS, APCAPS, and IHDS (though IHDS only include anthropometric data, whereas IMS and APCAPS measured a range of health outcomes). However, even within the recommended uses of these data, additional limitations may exist for populations with unique dietary needs or intake patterns, such as children (for whom 24HR or FFQ would require knowledgeable respondent proxies, and difficult assumptions about individual allocation from household-level surveys) and minority populations (where FFQ may not be reflective of unique cultural foods). Users of these data sources should therefore examine their suitability for purposes other than what the data were originally designed for. The most precise method for energy intake remains doubly-labelled water, and 7-day weighed food records for micronutrient intake, though their use is limited by their cost and time requirements.

As such, there may be a tradeoff between feasibility of national coverage and accuracy of individual-level intake. These above points apply to any uses of the data, including for research or programmatic needs.

This comparison of Indian dietary data has some limitations. First, it is not possible to validate the individual data sources as no gold standard reference exists for our use, and therefore our comparisons between sources are only in relative terms. We have matched data for major characteristics such as year, region, sex, and socioeconomic levels, though other sampling factors may have contributed to the differences in intake we have calculated, particularly for the non-nationally representative data sources. The availability of data meant we could not compare all survey types against each other for a given time period, and for this reason, we used the expenditure surveys, for which several rounds are available, as the common reference comparison to other data sources. The year of the data source may have differentially affected our comparisons, for example, as increasing consumption out of home may have exacerbated differences between HCES and FBS for the more recent time period. All data sources, except the FBS, are also likely to suffer to some degree from recall bias. The conversion of HCES intake data from the household to individual level may have introduced some bias, as differences in intra-family food allocation likely exist(44) outside of age- and sex- derived energy requirements. However, despite these limitations, this is the first comparative analysis to bring these varied data sources together, and this work should serve as a useful platform to inform the many future uses of these data.

This analysis compares estimated food intake across several Indian data sources to contextualise broad relative differences across dietary intake estimation methods. Each methodological choice may have its own advantages and disadvantages for particular research uses, and further work is required to suggest specific improvements for current Indian dietary data sources. Of general usefulness would be the development of more comprehensive nutritional composition databases, and improved methods in the on-going national surveys for measuring food consumption out of home. Also crucial is generation of high-quality data that can be used to validate or calibrate the various current and future sources of dietary intake.

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Conflict of interest

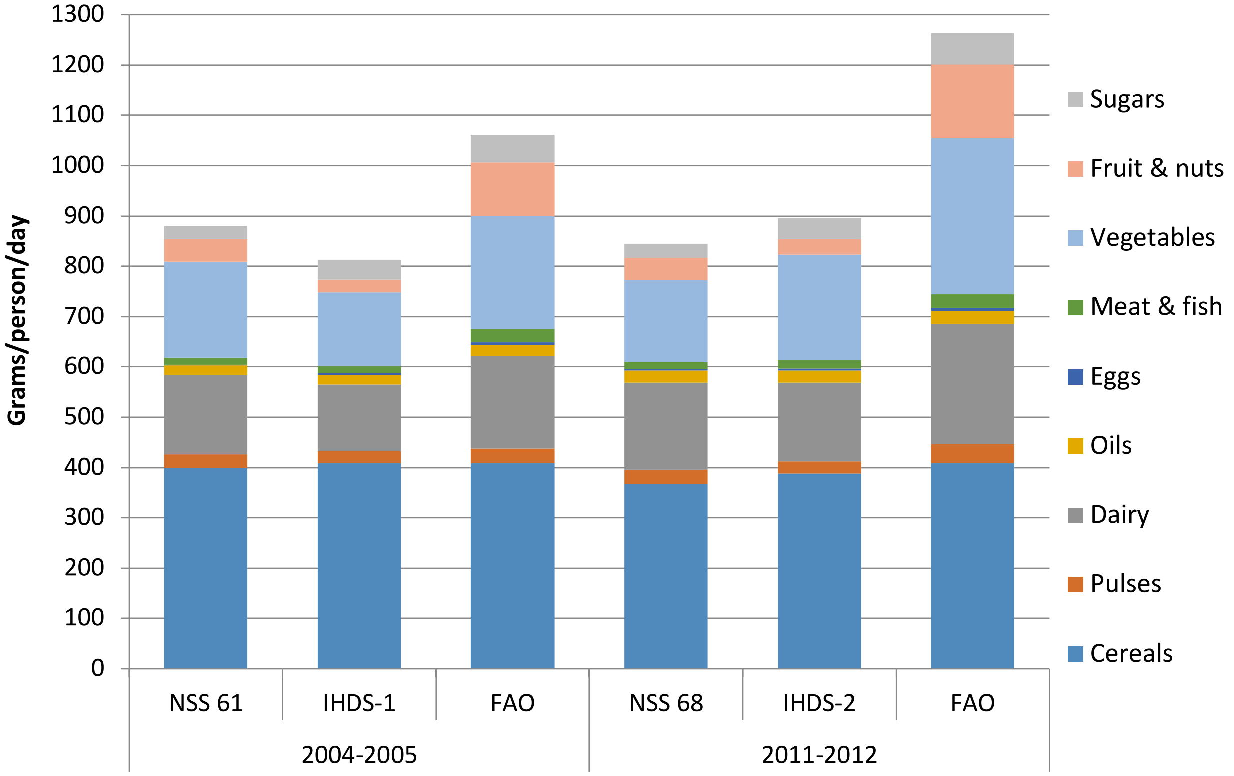
The authors declare that there are no conflicts of interest.

Authorship

LA and MT designed the study, and LA carried out the analysis, and drafted the paper. SK was involved in data collection of the APCAPS, and shared the IMS and APCAPS data. LA has primary responsibility for the final content. All authors were involved in data interpretation, critical revisions of the paper, and approved the final version.

Figures

Figure 1: Consumption of food groups at the national level, recorded in household expenditure surveys (NSSO, IHDS) and food balance sheets (FAO), in 2004-5 and 2011-12.



Tables

Table 1: Description of datasets.

	Data type	Year of survey	Region	Rural/ urban	Recall period	Sample size
NSS 61	HCES	2004-2005	National	Both	30 days	353,561
NSS 66	HCES	2009-2010	National	Both	30 days	284,718
NSS 68	HCES	2011-2012	National	Both	30 days	285,954
NSS 68 type 2	HCES	2011-2012	National	Both	7 days*	285,695
IHDS-1	HCES	2004-2005	National	Both	30 days	124,355
IHDS-2	HCES	2011-2012	National	Both	30 days	121,622
IMS	FFQ	2005-2007	Hyderabad, Lucknow, Nagpur, Bangalore districts	Both	1 year	4,531
APCAPS-3	FFQ	2010-2012	Rangareddy district, Andhra Pradesh	Rural	1 year	6,273
NNMB	24HR	2004-2005	National**	Rural	24 hours	N/A
NNMB	24HR	2011-2012	National**	Rural	24 hours	N/A
FAO	FBS	2005-2006	National	Both	N/A	N/A
FAO	FBS	2011-2012	National	Both	N/A	N/A

NSS, National Sample Survey; HCES, Household consumption expenditure survey; IHDS, India Human Developent Study; IMS, Indian Migration Study; FFQ, food frequency questionnaire; APCAPS, Andhra Pradesh Child and Parent Study; NNMB, National Nutrition Monitoring Bureau; 24HR, 24-hour recall; FAO, Food and Agriculture Organisation; FBS, food balance sheets.

*7-day recall for meats, eggs, oils, fruits, vegetables; 30-day recall for cereals, pulses, sugar.

**Data collected in 10 Indian states, sample not designed to be nationally-representative.

Table 2: Relative differences in absolute intake of all food groups (g/person/day) between survey types.

Reference survey	Intake g/d	Comparison survey	Intake g/d	% Difference
HCES vs. HCES (avg.)				**-1%**
NSS 61	881	IHDS-1	813	-8%
NSS 68	845	IHDS-2	895	6%
FFQ vs. HCES (avg.)				**13%**
IHDS-1	996	IMS	1052	6%
NSS 66	735	APCAPS	891	21%
FBS vs. HCES (avg.)				**35%**
NSS 61	881	FAO	1061	20%
NSS 68	845	FAO	1263	50%
IHDS-1	813	FAO	1061	31%
IHDS-2	895	FAO	1263	41%
24HR vs. HCES (avg.)				**-9%**
IHDS-1	735	NNMB	745	1%
IHDS-2	862	NNMB	712	-17%
NSS 61	807	NNMB	745	-8%
NSS 68	814	NNMB	712	-13%

HCES, Household consumption expenditure survey; NSSO, National Sample Survey Organistion; IHDS, India Human Developent Study; FFQ, food frequency questionnaire; IMS, Indian Migration Study; APCAPS, Andhra Pradesh Child and Parent Study; FBS, food balance sheets; FAO, Food and Agriculture Organisation; 24HR, 24-hour recall; NNMB, National Nutrition Monitoring Bureau.

Table 3: Relative differences in intake (g/person/day) of food groups between survey types

	HCES vs. HCES	FFQ vs. HCES	FBS vs. HCES	24HR vs. HCES	Average*
Cereals	4%	-1%	5%	9%	5%
Pulses	-10%	41%	31%	25%	27%
Dairy	-13%	49%	37%	-34%	33%
Fats	1%	15%	11%	-28%	14%
Eggs	60%	212%	87%	N/A	119%
Meat & fi:	11%	114%	83%	-17%	56%
Vegetable	3%	-24%	52%	-26%	26%
Fruit & nu	-36%	182%	264%	-1%	120%
Sugar	44%	-24%	78%	-55%	50%

HCES, Household consumption expenditure survey; FFQ, food frequency questionnaire; FBS, food balance sheets; 24HR, 24-hour recall.

*Absolute magnitude, taking all relative differences as positive.

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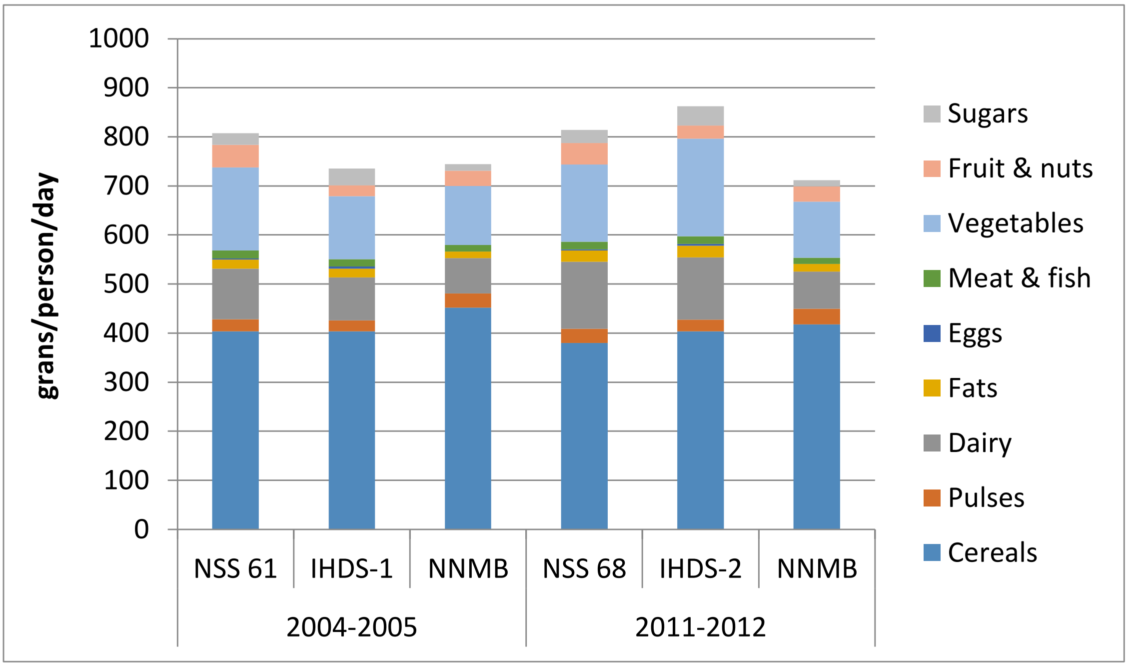
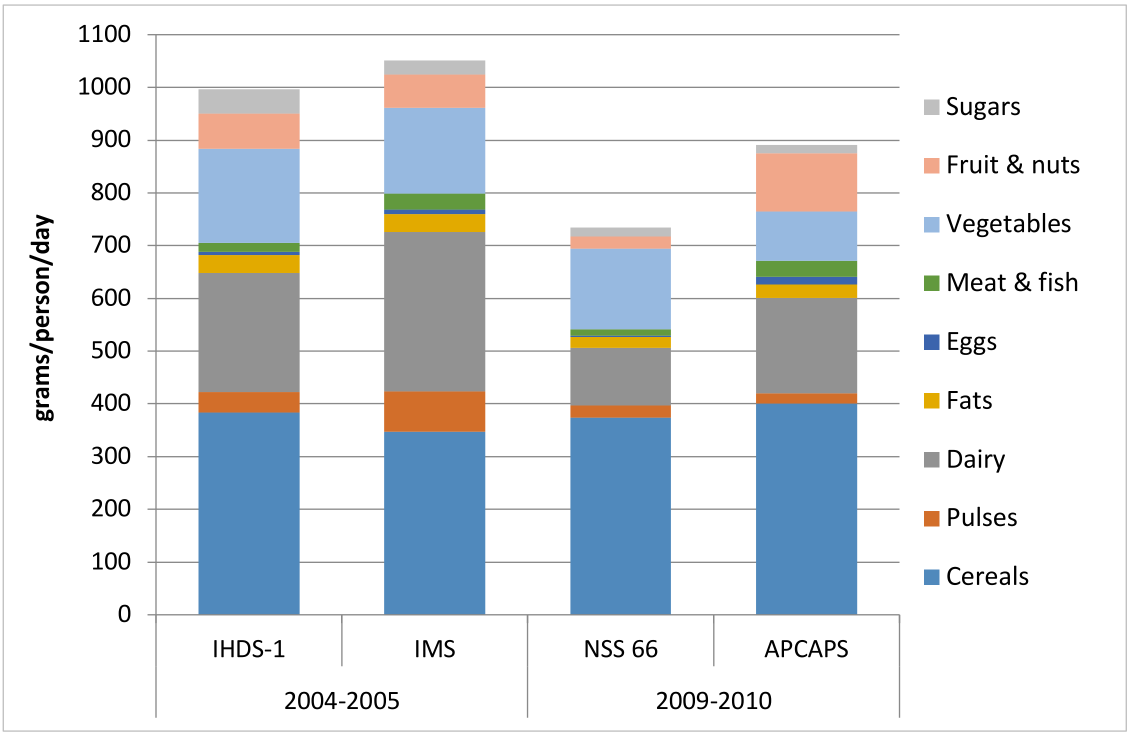
Supplementary material

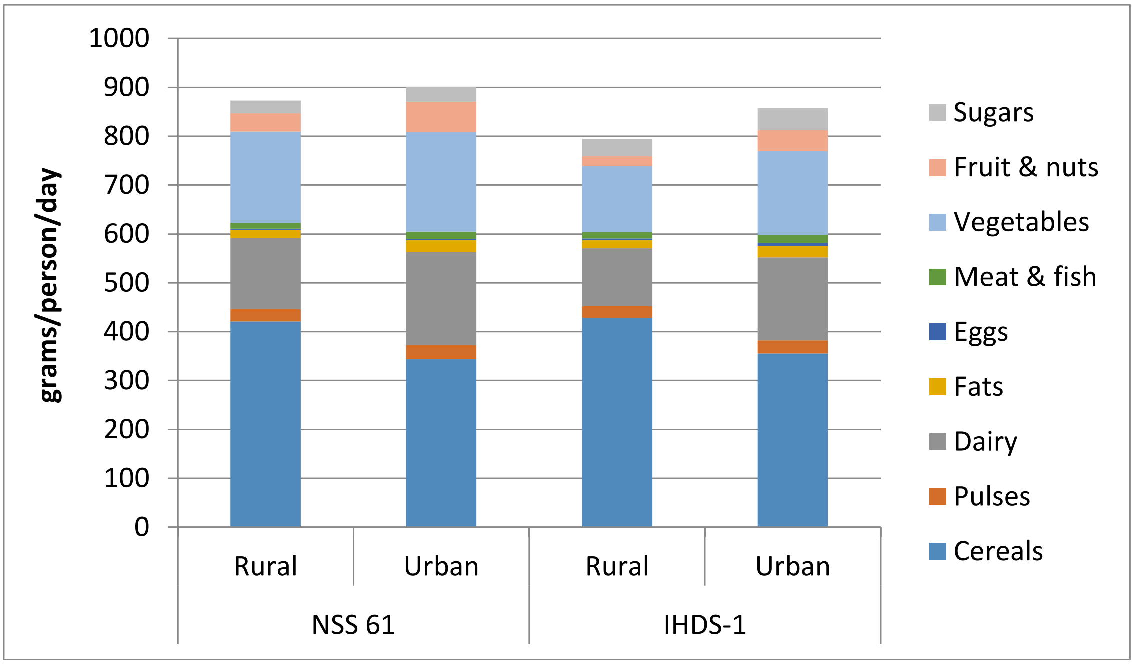
Supplementary Figure 1: Consumption of food groups in rural regions of 10 Indian states, recorded in household expenditure surveys (NSSO, IHDS) and 24hr survey (NNMB), in 2004-2005 and 2011-2012.



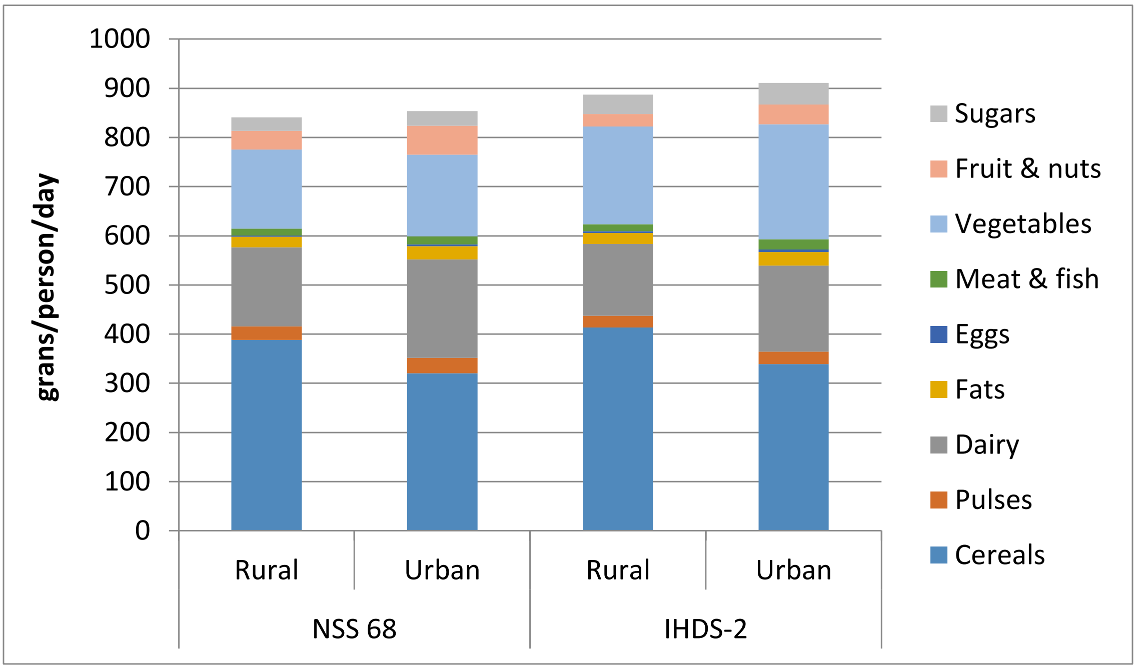
Supplementary Figure 2: Consumption of food groups recorded in FFQs (IMS and APCAPS) and household expenditure surveys (NSS and IHDS) in 2004-2005 and 2009-2010.



Supplementary Figure 3: Food consumption of food groups at the national level, by urban and rural regions, recorded in household expenditure surveys (NSSO, IHDS), in 2004-5.



Supplementary Figure 4: Food consumption of food groups at the national level, by urban and rural regions, recorded in household expenditure surveys (NSSO, IHDS), in 2011-12.



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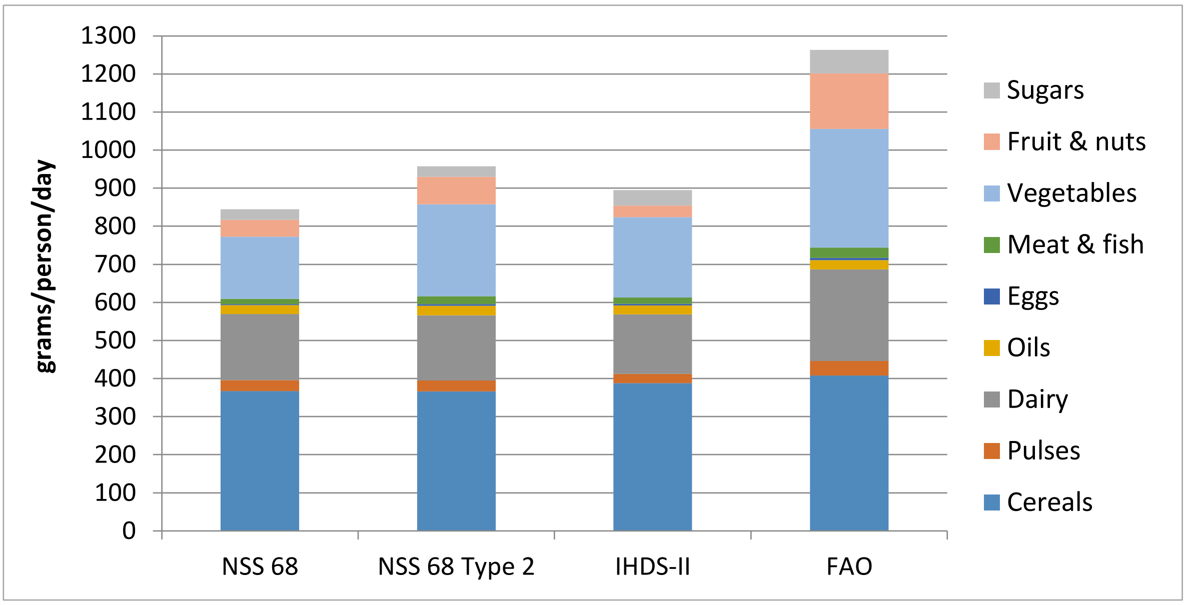

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First Name(s)	Lukasz		
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Primary Supervisor	Prof Sir Andy Haines		

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SECTION E

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Environmental impacts of dietary shifts in India: a modelling study using nationally-representative data

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Abstract

Food production is a major driver of environmental change, and unhealthy diets are the leading cause of global disease burden. In high-income countries (HICs), modelling studies suggest that adoption of healthy diets could improve population health and reduce environmental footprints associated with food production. We assessed whether such benefits from dietary change could occur in India, where under-nutrition and overweight and obesity are simultaneously prevalent.

We calculated the potential changes in greenhouse gas (GHG) emissions, blue and green water footprints (WFs), and land use (LU), that would result from shifting current national food consumption patterns in India to healthy diets (meeting dietary guidelines) and to "affluent diets" (those consumed by the wealthiest quartile of households, which may represent future purchasing power and nutritional trajectories). Dietary data were derived from the 2011-12 nationally-representative household expenditure survey, and we assessed dietary scenarios nationally and across six Indian sub-regions, by rural or urban location, and for those consuming above or below recommended dietary energy intakes. We modelled the changes in consumption of 34 food groups necessary to meet Indian dietary guidelines, as well as an affluent diet representative of those in the highest wealth quartile. These changes were combined with food-specific data on GHG emissions, calculated using the Cool Farm Tool, and WF and LU adapted from the Water Footprint Network and Food and Agriculture Organization, respectively.

Shifting to healthy guidelines nationally required a minor increase in dietary energy (3%), with larger increases in fruit (18%) and vegetable (72%) intake, though baseline proportion of dietary energy from fat and protein was adequate and did not change significantly. Meeting healthy guidelines slightly increased environmental footprints by about 3-5% across GHG emissions, blue and green WFs, and LU. However, these national averages masked substantial variation within sub-populations. For example, shifting to healthy diets among those with dietary energy intake below recommended guidelines would result in increases of 28% in GHG emissions, 18 and 34% in blue and green WFs, respectively, and 41% in LU. Decreased environmental impacts were seen among those who currently consume above recommended dietary energy (-6 to -16% across footprints). Adoption of affluent diets by the whole population would result in increases of 19-36% across the environmental indicators. Specific food groups contributing to these shifts varied by scenario. Environmental impacts also varied markedly between six major Indian sub-regions.

In India, where undernutrition is prevalent, widespread adoption of healthy diets may lead to small increases in the environmental footprints of the food system relative to the status quo, although much larger increases would occur if there was widespread adoption of diets currently consumed by the wealthiest quartile of the population. To achieve lower diet-related disease burdens and reduced environmental footprints of the food system, greater efficiency of food production and reductions in food waste are likely to be required alongside promotion of healthy diets.

Keys words: India, dietary intake, sustainable diets, dietary guidelines, greenhouse gas emissions, land use, water use

Introduction

Food production contributes globally to 19-29% of greenhouse gas (GHG) emissions, 70% of freshwater withdrawals, and uses one-third of ice-free land[1-3]. Food systems face an unprecedented challenge of providing an estimated 60% more food by 2050 to feed a growing and more prosperous population, while food production will likely face increased pressures from climatic and environmental change[4 5]. Current diets in high-income countries (HICs) contain excess dietary energy and high intakes of animal-based foods, resulting in high *per capita* environmental footprints[6 7]. A growing body of evidence has highlighted the mitigation potential of shifting current HIC diets to those which are healthier and reduce environmental impacts[8-10]. A variety of more environmentally sustainable dietary patterns have been proposed, with possible reductions in environmental footprints of 30-50% for vegetarian diets[8]. Achieving widespread uptake of these diets may be challenging, though modest environmental benefits could also be achieved by shifting to national dietary guidelines, which are currently widely supported, and potentially easier to adopt. However, little is known about the impacts of such options in low- and middle-income countries (LMICs)[8 11].

Globally, around 45% of countries have significant levels of both under-nutrition and overweight/obesity; approximately 2 billion individuals are overweight or obese, and 800 million have inadequate dietary energy intake[12]. In this context, increased adoption of healthy diets is critical to reducing all forms of malnutrition, though the impact of such dietary changes on various environmental pressures is uncertain. For example, high-income households may benefit from reducing overall dietary energy intake and replacing at least some consumption of animal-based foods with plant-based foods. In contrast, an increase in diet-related environmental footprints may be necessary for those households aiming to reach adequate dietary energy and diversity. Understanding these dynamics is important to guide policies that will deliver healthy diets and improved nutrition for all individuals, within climate and other planetary boundaries[4 13].

India is home to almost one-fifth of the global population, and has high rates of undernutrition (including one-third of the world's cases of child stunting) coinciding with growing rates of obesity and non-communicable diseases (NCDs)[14-16]. The country also faces critical environmental pressures on its ability to produce food. Despite its large share of the global population, it covers only 2.4% of the world's land[17], and agricultural irrigation accounts for 90% of freshwater use despite depleting groundwater reserves in some regions[18 19]. Although *per capita* GHG emissions are relatively low, India is the 4th highest contributor to global GHG emissions, behind China, the US, and the EU[20], and has committed to reducing emissions under the Paris Climate Agreement[21]. Indian diets are transitioning away from staple foods, such as pulses and coarse cereals, to vegetable- and animal-based fats, and energy-dense, highly processed foods[22-24], though dietary energy from cereals still remains high[25]. As incomes continue to rise, diets are projected to both diversify nutritionally and include excess dietary energy, particularly from oils, meat, dairy, and sugar[26 27]. Globally, these changes may increase the number of obese individuals from 1.33 billion in 2005 to 3.28 billion by 2030, with Asia leading in the transition from dietary energy insufficiency to excess[28]. Economic growth alone will not necessarily improve nutrition[28], and projected dietary changes may also further compound existing environmental pressures.

Recent work has shown that the much-needed shifts to healthy diets in selected Indian regions could partially buffer water-related pressures facing agricultural production, and decrease GHG emissions[29], and a national study also concluded that heathy dietary shifts could reduce GHG emissions[30]. Here, we extend this work by combining, for the first time, nationally-representative dietary data with food-specific GHG emissions, water footprints (WFs), and land use (LU), to assess multiple environmental indicators. We explore two scenarios – a shift to healthy diets, and a shift to “affluent” diets, a perspective that has not previously been studied – to assess the environmental opportunities and challenges of food systems to meet dietary needs in India.

Methods

Data

Dietary data were derived from the 68th round of the Indian National Sample Survey (NSS), a nationally-representative household consumer expenditure survey conducted in 2011-12 (n=101,651 households)[31]. The questionnaire records the quantity and value of approximately 140 food, meal and beverage items purchased by the household within the last month, among other consumer goods, and we used the quantity of food purchased and produced for own consumption as a proxy for intake. We used the improved “type 2” format of the survey which used 7-day recall for meats, eggs, oils, fruits and vegetables, and 30-day recall for cereals, pulses and sugar. This survey is the only nationally-representative source of quantitative dietary data in India[32].

Household-level data on quantity of food purchased was divided out among household members to approximate individual-level intakes, using Indian energy requirement consumption units based on age and sex, as provided in the NSS documentation[31] (the survey included household members of all ages). We adjusted household intake for meals received by members (school meals, payment for labour, etc.), and/or provided to non-household members (further details in Supplementary file 1). These are recorded separately from the food expenditure and would otherwise skew the amount of food available for household consumption from the recorded expenditure; for context, approximately 23% of households received a net positive amount of meals, while 38% provided more meals than received. We calculated dietary energy, protein and fat intake using nutritional composition data provided by NSS documentation for each of the 134 food items, and aggregated the intake of these items into 34 food groups based on nutritional content similarity (details of groupings are provided in the Supplementary table 1). Individuals consuming below 200 or above 5000 kcal/day were excluded (n=1829), and our final sample of individuals was 462,901. We additionally adjusted intake of the 34 food groups to approximate food group intake from meals eaten out of home (on average, 18% of households' dietary energy; additional details in Supplementary file 1). We used household sample weights in our tabulation of baseline intake of the 34 food groups. We then linked each food group to estimates of GHG emissions, blue and green WFs, and LU associated with the production of food items.

We used existing data on GHG emissions (kg CO_2-eq/kg food product) that had been derived for the food groups used in this analysis[33]. The values are based on emissions associated with the agricultural production stage of major crops and livestock products, estimated with a derivative of the Cool Farm Tool (CFT)[34 35], using Indian farm-level activity data obtained from the Directorate of Economics and Statistics of the Government of India (http://eands.dacnet.nic.in). The set of empirical models making up CFT use inputs on soil, climate, and farm management, including fertiliser, pesticide and herbicide use, residue management, machinery, and energy use. Emissions from rice production were calculated using the approach of Yan et al. (2005)[36]. National-level emission averages were used for food items. CFT was used to derive emissions directly for 22 out of our 34 food groups. For groups that could not be assessed as above, production-stage emissions were derived from the literature, or a CFT-derived proxy was allocated. Production stage emissions were then combined with post-production stage emissions, also based on review of the literature[33]. Where two or more items were aggregated within a food group (i.e., other pulses, other cereals, ruminant meats, etc.), footprints were weighted by the quantity of the individual items consumed. Further details of these data have been published[33 35].

Data on India-specific WFs (L/kg food product) were used from a previous study that derived footprints for the same food groups and items used in this analysis. The existing values were adapted from a database made publicly available by the Water Footprint Network (WFN)[37 38] (http://waterfootprint.org/en/resources/water-footprint-statistics/). Individual product footprints from the WFN data were matched to food groups based on author judgement, and the total footprint of a food group was weighted by the quantity of consumption of individual items within the group. To account for geographical differences in WF values throughout India, we used national values that had weighted average state-level values by land area (see Harris et al. 2017, for description of methods[39]). We assessed both blue (ground and surface) and green (rainfall) WFs.

Land use (m^2/kg food product) for crops within our food groups was derived directly from FAO yield data for India for the year 2014[40]. For livestock products, FAOSTAT publish data on yields per head of livestock but not yields per unit area of land. Thus, yield data for livestock products were calculated on the basis of livestock feed requirements[38], yields of feed crops and fodder[40 41], and feed conversion efficiencies. Nationally, <1% of feed is imported[40] so it was assumed that all feed was grown in India. We include a more comprehensive description of the land use footprint calculations in Supplementary file 1.

We include food group-specific footprint values for all indicators in Supplementary table 2.

Scenario analysis

We measured the change in environmental footprints between current average diets, and two dietary scenarios of shifting to national healthy guidelines, and to affluent diets. We modelled the healthy diets scenario nationally, and for several sub-national samples, including by region (north, north-east, east, south, west, central), rural or urban residence, and for those whose estimated individual-level dietary energy was below (BRI) or above

(ARI) recommended age- and sex-specific energy intake. The BRI and ARI groups were meant to represent a simplified picture of the dual challenges of under-nutrition and overweight/obesity, and to highlight broad dietary and environmental changes required to bring these sub-groups to a healthy diet scenario. The affluent diet scenario was assessed for all the same sub-national samples, except for the BRI and ARI groupings. We calculated both relative and absolute changes in environmental footprints, per capita per day.

Table 1: Selected dietary characteristics by Indian regions (per capita).

	North	North east	East	South	West	Central	India
Proportion of population	8%	4%	22%	22%	15%	30%	-
Mean energy intake (kcal)	2337	2064	2139	2093	2091	2158	2141
Dietary guidelines target*	*2236*	*2253*	*2201*	*2232*	*2236*	*2178*	*2211*
Mean vegetable intake (g)	197	164	170	149	151	137	155
Dietary guidelines target*	*269*	*271*	*265*	*270*	*269*	*262*	*266*
Mean fruit intake (g)	82	53	44	156	105	52	83
Dietary guidelines target*	*97*	*98*	*98*	*97*	*97*	*98*	*98*
% energy from protein	12%	11%	11%	11%	11%	12%	11%
% energy from fat	25%	13%	15%	21%	27%	19%	20%
% calories from							
Cereals	50%	73%	68%	58%	51%	63%	61%
Pulses	5%	4%	4%	6%	8%	5%	5%
Meat (egg, fish)	1%	3%	2%	3%	1%	1%	1%
Dairy	17%	3%	4%	7%	9%	9%	8%
Fruit and veg	5%	4%	4%	8%	6%	4%	5%
Oils	11%	8%	9%	11%	16%	10%	11%
Other	11%	6%	9%	6%	10%	9%	8%

Note: *As the dietary guidelines are age- and sex-specific, the guideline target is age- and sex-weighted for each region. Targets for dietary energy from protein and fat were recommended as 10-15% and 20-30%, respectively. Regions defined as: North (Chandigarh, Delhi, Haryana, Himachal Pradesh, Jammu & Kashmir, Punjab, Uttarakhand); North-East (Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim, Tripura); East (Bihar, Jharkhand, Orissa, West Bengal); South (Andhra Pradesh, Andaman & Nicobar Islands, Karnataka, Kerala, Lakshadweep, Puducherry, Tamil Nadu); West (Dadra & Nagar Haveli, Daman & Diu, Goa, Gujarat, Maharashtra); Central (Chattisgarh, Madhya Pradesh, Rajasthan, Uttar Pradesh). Population proportions sum to 101% due to rounding.

Dietary guidelines were taken from the Indian National Institute of Nutrition (NIN)[42], using guidelines on total energy intake (assuming moderate physical activity), % energy from protein and fat (recommended as 10-15 and 20-30%, respectively), and adequate fruit and vegetable intake (excluding intake of potatoes). Dietary energy, fruit and vegetable intake guidelines varied by age and sex (Supplementary table 3). These guidelines match those of the WHO[43]. The age and sex distribution of each of the regional, rural or urban, and BRI/ARI sub-samples was used to create relevant weighted dietary guidelines for each sub-sample.

A healthy diet was optimised for each population sub-sample, with the primary function of minimising deviation from the current diet (the summed and squared relative difference across all food groups) to keep dietary change as realistic as possible[44]. Intake of each of the 34 food groups were the variables optimised in the model, and these were also weighted by their relative share of intake in the diet. Our optimisation model minimised the following function:

$$\left((p_1)\frac{x_{b1}-x_{s1}}{x_{b1}}\right)^2+\left((p_2)\frac{x_{b2}-x_{s2}}{x_{b2}}\right)^2+\cdots\left((p_n)\frac{x_{bn}-x_{sn}}{x_{bn}}\right)^2$$

where x is the intake (grams per day) of food items 1, …,*n*, for optimised healthy (x_s) and baseline (x_b) diets, and p is the proportion of that food item by weight in the diet. We additionally constrained the model to meet the age- and sex-weighted dietary guidelines described above (Supplementary table 3), and restricted the relative change in intake of any food group to less than 50%.

Rising incomes are associated with shifts to both greater dietary diversity and excess dietary energy, sugar, and salt intake[45], and we modelled an “affluent diet” scenario to explore how rising incomes may impact diet-related environmental footprints. This scenario assumed the universal adoption of diets that are currently typical of high-income households, which we approximated as the top quartile of households in terms of mean *per capita* expenditure (MPCE). We generated household MPCE quartiles separately within each of the six Indian regions described above, and by rural or urban residence (twelve total stratifications). Within each of the twelve regional stratifications, individuals from non-affluent households were then assigned the same diets as those from the affluent households, matched for age and sex (e.g. diets of non-affluent individuals from rural central India were shifted to the age- and sex-matched diets of affluent individuals of rural central India). The changes in environmental impacts from this shift were then calculated. We did not conduct a measure of statistical significance, as using the national diet expenditure data results in very small margins of error (while the real uncertainty is likely much larger and a function of measurement error rather than sample size[46]), and standard errors were not available in all the environmental footprint data.

Optimisation of healthy diets was modelled using Microsoft Excel's Solver package (specifically using the GRG non-linear algorithm). All other calculations were performed using STATA 13.0.

Results

Current average diets

Current average intake in India was below recommended guidelines for dietary energy (2141 vs. 2211 kcal/*capita*/day), and fruit and vegetable intake (155 vs. 266 g/*capita*/day, and 83 vs. 98 g/*capita*/day, respectively) (Table 1). The north region was the only exception (comprising the states of Chandigarh, Delhi, Haryana, Himachal Pradesh, Jammu & Kashmir, Punjab, and Uttarakhand), with average intake of dietary energy above recommended levels. Average percentage of dietary energy from protein and fat were adequate nationally, though fell short for fat in some regions. Cereals made up the largest contribution to dietary energy. Contribution from meat was low for all regions (1-3%), while that for dairy varied greatly across regions, ranging from 3% in the north-east to 17% in the north region (Table 1). Compared to national average intake, the BRI population sample had a larger gap between current and recommended consumption of fruit and vegetables, and a higher proportion of dietary energy from cereals. Conversely, compared to national average intake, the ARI sample had greater intake of all 34 food groups assessed, resulting in dietary energy intakes well above recommended guidelines (2534 vs. 2131 kcal/*capita*/day, respectively), with adequate fruit intake, and vegetable consumption greater than the national average but below that recommended by guidelines (Table 2). Mean diet-related environmental footprints nationally per capita per day were 1.3 kgCO_2-eq, 0.5 m^3 blue WFs, 1.6 m^3 green WFs, and 3.9 m^2 land use (Supplementary table 4). Food groups which contributed most to diet-related environmental footprints in India were as follows: dairy for GHG emissions, wheat for blue water footprint, rice for green water footprint, and vegetable oils for land use (Supplementary figure 1).

Shifts to healthy diets

Shifts from current average intakes to healthy diets at the national level would result in a small increase of 4% in GHG emissions and LU, and 3 and 5% in blue and green WFs, (and absolute increases of 0.06 kgCO_2-eq in emissions, 0.02 m^3 blue WFs, 0.08 m^3 green WFs, and 0.17 m^2 LU), respectively (Figure 1, Supplementary table 4). The dietary change required to achieve a healthy diet was largely characterised by increased vegetable intake (Supplementary figure 2).

However, there were substantial differences in direction of change of environmental footprints among populations below and above recommended dietary energy intake. For those currently below recommended guidelines, the additional agricultural production required to meet healthy guidelines would result in increases of 28% in

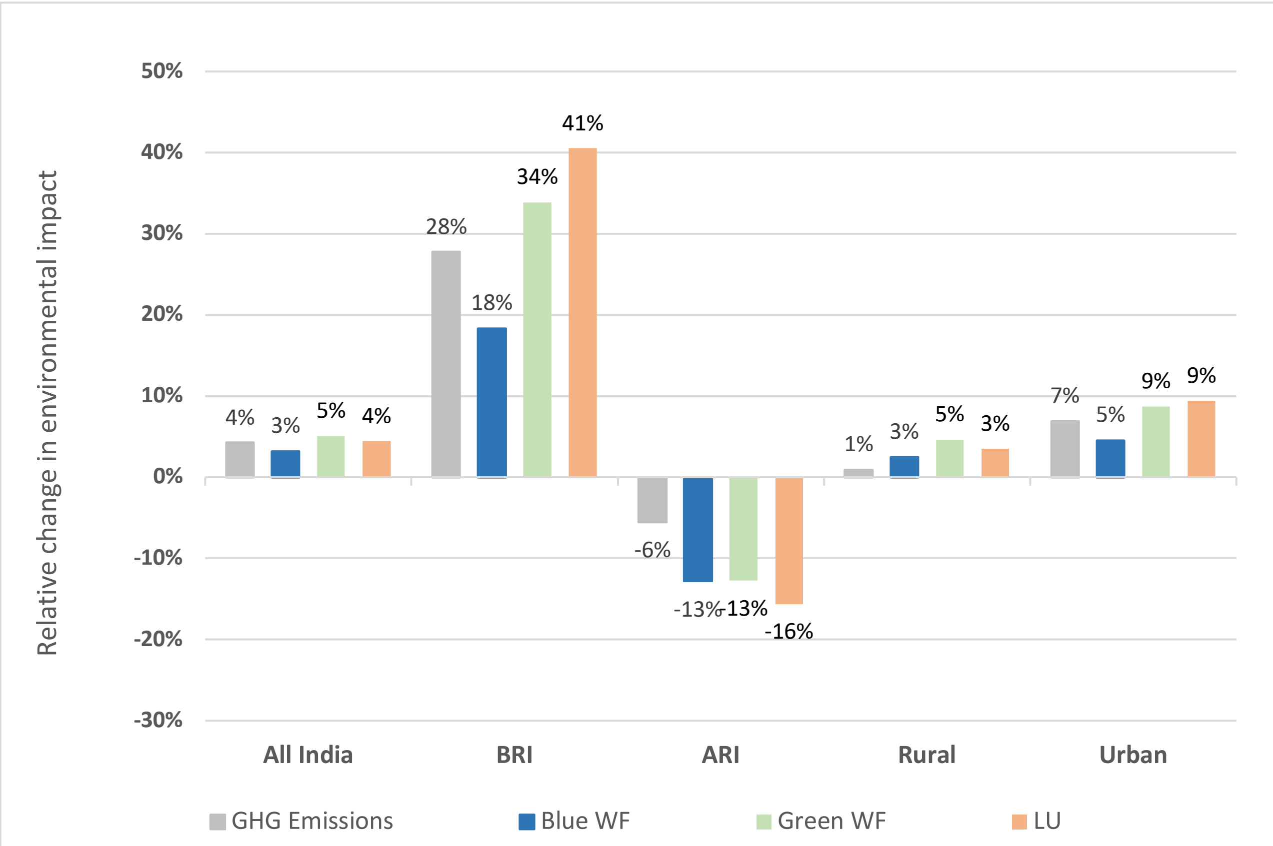
Table 2: Selected dietary characteristics of Indian population sub-samples and scenarios used in analysis.

	India	India rural	India urban	BRI	ARI	Affluent
Proportion of Indian population	-	71%	29%	58%	42%	25%
Mean energy (kcal)	2141	2150	2119	1855	2534	2477
Dietary guidelines target	*2211*	2197	2244	*2269*	*2131*	-
Mean vegetable intake (g)	155	150	165	134	183	191
Dietary guidelines target	*266*	*265*	*270*	*272*	*258*	-
Mean fruit intake (g)	83	63	134	59	116	163
Dietary guidelines target	*98*	*98*	*98*	*98*	*97*	-
% energy from protein	11%	11%	11%	11%	11%	11%
% energy from fat	20%	18%	24%	19%	21%	23%
% calories from						
Cereals	61%	64%	53%	63%	59%	53%
Pulses	5%	5%	6%	5%	5%	6%
Meat (egg, fish)	1%	1%	2%	1%	1%	2%
Dairy	8%	7%	10%	7%	10%	12%
Fruit and veg	5%	4%	7%	5%	6%	7%
Oils	11%	10%	13%	11%	11%	11%
Other	8%	8%	9%	8%	9%	9%

Note: BRI, estimated individual-level dietary energy below recommended age- and sex-specific intake; ARI, dietary energy above recommended intake; Affluent, diets of the top quartile of the population according to monthly per capita expenditure. Targets for dietary energy from protein and fat were recommended as 10-15% and 20-30%, respectively. Targets not shown for affluent diet as it was not optimised for health.

GHG emissions, 18 and 34% in blue and green WFs, respectively, and 41% in LU (Figure 1, Supplementary figure 3); in absolute terms, equating to increases of 0.31 kgCO_2-eq in emissions, 0.09 m^3 blue WFs, 0.46 m^3 green WFs, and 1.39 m^2 LU (Supplementary table 4). Meeting dietary guidelines in this sample required increases across a range of food groups (particularly fruit, pulses, vegetables and vegetable oil), while the environmental impacts of this shift were largely driven by meat and vegetables for GHG emissions, vegetable oils and meat for LU, while more distributed across cereals, fruit, meat, vegetables, pulses and vegetables oils for blue and green WFs (Tables 2 and 3).

Figure 1: Relative change in greenhouse gas (GHG) emissions, water footprints (WFs), and land use (LU), from shifting current average Indian diets in different population groups to healthy guidelines.



Note: BRI, estimated individual-level dietary energy below recommended age- and sex-specific intake; ARI, dietary energy above recommended intake; GHG, greenhouse gas; WF, water footprint; LU, land use.

Table 3: Relative contribution of food groups to changes in greenhouse gas (GHG) emissions, water footprints (WFs) and land use (LU) in the dietary change scenarios.

	India								BRI				ARI			
	Shift to healthy diets				Shift to affluent diets				Shift to healthy diets				Shift to healthy diets			
	GHG	Blue WF	Green WF	LU	GHG	Blue WF	Green WF	LU	GHG	Blue WF	Green WF	LU	GHG	Blue WF	Gree n WF	LU
	% change															
Cereals	3	6	4	4	-2	15	-3	-1	7	17	11	8	-69	-70	-47	-34
Dairy	1	0	0	0	56	30	26	24	2	1	0	0	-13	-2	-2	-1
Butter	2	1	1	1	3	2	1	1	5	2	1	1	0	0	0	0
Fish	0	0	0	0	1	2	1	0	0	0	0	0	-1	0	0	0
Fruit	7	20	13	7	3	17	17	7	3	13	6	3	-2	-2	-2	-1
Meat	15	2	3	7	30	9	15	25	52	9	10	16	-6	-1	-2	-2
Egg	1	2	2	2	0	3	5	4	2	10	8	6	0	0	0	0
Pulses/leg	2	1	4	6	2	2	7	9	8	5	10	11	-14	-4	-13	-15
Veg/tuber	68	56	55	44	3	5	6	3	16	14	12	7	22	10	14	5
Veg oils	2	7	16	28	1	5	17	24	4	18	38	47	-8	-10	-40	-49
Sugar	1	4	1	0	1	8	2	1	1	10	2	1	-10	-21	-7	-3
Nuts	0	0	1	0	0	1	2	1	0	1	2	1	0	0	0	0
Spices	0	0	0	0	1	1	4	2	0	0	0	0	0	0	0	0

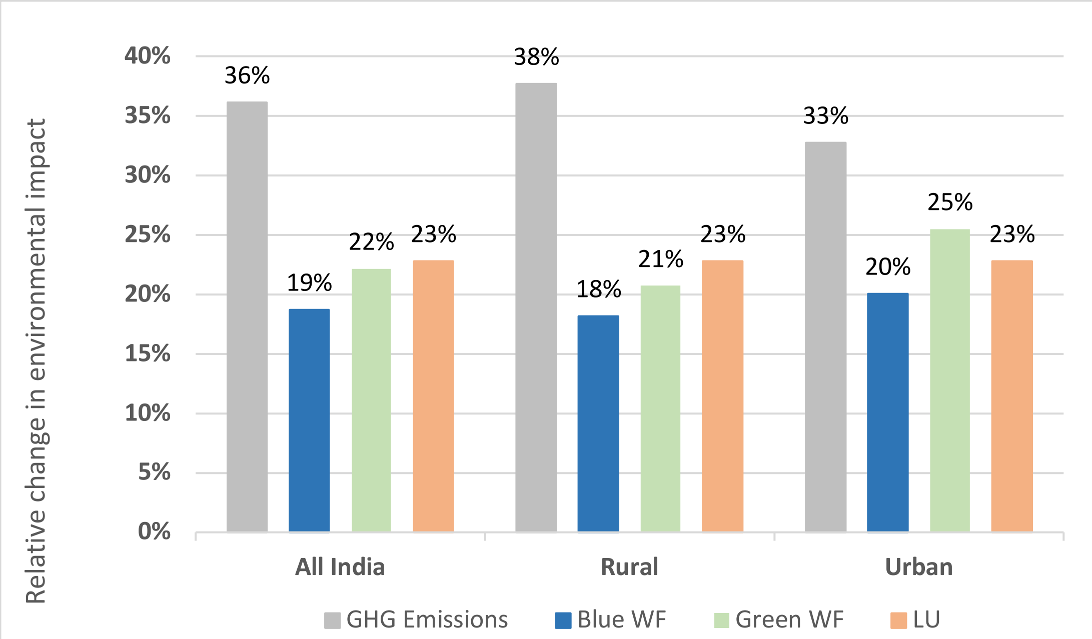
Note: BRI, estimated individual-level dietary energy below recommended age- and sex-specific intake; ARI, dietary energy above recommended intake; GHG, greenhouse gas; WF, water footprint; LU, land use.

Conversely, for populations above recommended dietary energy intake, decreases of 6% in GHG emissions (-0.09 kgCO_2-eq), 13% in blue and green WFs (-0.08 and -0.23 m^3, respectively), and 16% in LU (-0.73 m^2) could be achieved by meeting healthy guidelines (Figure 1, Supplementary table 4). This scenario was largely characterised by lower absolute intake of cereals and sugar in exchange for higher vegetable intake (Supplementary figure 4), and the decreases in environmental footprints were mostly due to lower intake of cereals (largely rice), as well as vegetable oils specifically for green WFs and LU (Tables 2 and 3).

Shifts to affluent diets

We modelled a change to affluent diets to provide a comparative scenario of dietary change based on economic growth, rather than efforts to converge intakes to healthy guidelines. Affluent diets were characterised by high dietary energy (2477 kcal/*capita*/day vs. an age- and sex-weighted recommended dietary energy of 2284 kcal/*capita*/day), high intake of fruit and vegetables (though the latter below guidelines), and compared to average Indian diets, higher dairy and meat intake, and proportion of energy from fats (Table 2). Shifting the entire Indian population to affluent diets would increase GHG emissions by 36% (0.48 kgCO_2-eq), blue and green WFs by 19 and 22% (0.10 and 0.35 m^3), respectively, and LU by 23% (0.90 m^2), with some difference in these changes between rural and urban areas (Figure 2). Relative to the small increases in environmental footprints required to improve diets nationally in the earlier healthy guidelines scenario, this comparative trajectory to affluent diets would result in substantially higher environmental footprints. This increase in footprints was largely due to higher intake of meat and dairy, while vegetable oils also contributed substantially to the increase in LU and green WFs, and fruit to the increase in blue WFs (Table 3).

Figure 2: Relative change in greenhouse gas (GHG) emissions, water footprints (WFs), and land use (LU), from shifting current average Indian diets to affluent diets.



Note: GHG, greenhouse gas; WF, water footprint; LU, land use.

Regional analysis

Environmental impacts for both healthy and affluent scenarios varied between the six major Indian sub-regions (Supplementary table 4). For example, shifts to healthy diets would reduce GHG emissions by 2% in the east, and increase emissions by 7% in the west region. The north would have the largest footprint reductions (-5 and -8% in green WFs and LU, respectively), while the north-east region would experience some of the largest increases (16 and 20% in green WFs and LU respectively). Shifts to affluent diets would increase environmental footprints in all regions. The largest increases would be seen in the central (40% for GHG emissions), south (23% for blue WFs), north (27% for green WFs), and north-east regions (28% for LU).

Discussion

This study estimates changes in environmental footprints that would result from shifting current national diets to scenarios of healthy or affluent diets, in the context of India's dual burden of under-nutrition and overweight/obesity. Given that dietary shifts could present trade-offs across environmental indicators[8], our study extends recent work in LMICs, and is the first to our knowledge to combine nationally-representative Indian dietary data with a range of environmental footprints. Modelling the important goal of adoption of healthy diets for all individuals nationally, we show that increases of about 20-40% across agricultural GHG emissions, blue and green WFs, and LU may be required to shift those currently below recommended dietary energy intake to healthy diets. However, these impacts could be balanced by the opportunity of decreased environmental footprints from healthy shifts among those above recommended dietary energy intake. Overall, only small increases in environmental footprints would result from shifting national-level intakes to diets which are healthy and diverse. Comparatively, a trajectory to affluent diets, typical of the nutrition transition unfolding in LMICs, would lead to additional footprints of 36%, 19%, 22% and 23% in GHG emissions, blue and green WFs, and LU, respectively.

Various food groups contributed to these shifts across the scenarios and sub-populations studied. For example, in a transition to an affluent diet, meat and dairy were largely responsible for the increase in all environmental footprints. A decrease in cereals and oils drove the environmental benefits of shifting the ARI subsample to healthy diets, while a broad diversification of increased intake across pulses, vegetables, and meat drove increases in footprints for the BRI subsample.

Many studies over the last decade have now assessed the potential of using dietary change to improve health and environmental outcomes, though this literature has almost exclusively been focused on HICs, and analyses at the global level have not specifically assessed the impacts of improving diets for potentially undernourished populations[8]. Recent work has begun to examine these relationships in LMICs[29 30 47-50]. In China, two recent analyses found that national shifts to healthy diets would decrease footprints; in one case, annual national GHG emissions and blue WFs reduced by $1.7 * 10^{12}$ g and $2.7 * 10^{13}$ L, respectively (comparatively, using the 2012 Indian population[51], our results indicated an annual national increase of $2.8 * 10^{13}$ g and $9.2 * 10^{12}$ L, respectively)[49], and a second analysis showed GHG emissions decreasing by about 12%[50]. These results are contrary to our analysis for India, though can likely be explained by China's lower rates of undernutrition[14 52], and a higher baseline intake of meat than in India, the reduction of which contributed to much of the environmental benefit of healthy diets. A study at the city level in Delhi assessed improving nutrition status for the poorest half of the population to that of the median income class, and found modest increases – 4-9% across the same three environmental indicators[53] – lower than those found here, as the dietary energy gap existing in their scenario was smaller than the one we examined. Milner et al. 2017, found that across several Indian regions, shifts to healthy diets could be protective against future water-related pressures facing agricultural production, and additionally decrease GHG emissions[29]. The most comparable study to ours, also using national data, concluded that meeting micronutrient requirements could reduce GHG emissions by 19%[30] (though a scenario of minimising deviation from baseline diets saw a smaller reduction); this contrasts with our results, which saw a small increase of 4%. This could be a function of several differences between our analyses, including underlying GHG values (the authors' animal-based food footprint values were greater than ours), a healthy diet definition focused on micronutrients compared to our use of absolute fruit and vegetable intake, and use of the 'type 1' NSS format compared to our use of 'type 2' (30-day vs. 7-day recall). Our healthy scenario optimisation minimised deviation from current intakes to model a realistic dietary shift; this healthy scenario was marked by little change in intake of cereals, with substantial increase in vegetable intake, and to a lesser extent, fruit. The analysis by Rao et al. highlighted that within cereals, shifts from fine rice to wheat and other coarse grains, could be another important route for health and environmental benefits[30].

We have highlighted dietary change among those who consume adequate dietary energy as a pathway to reducing environmental footprints. However, given the importance of improving nutrition for all within current environmental pressures, this demand-side approach should be viewed as only one pathway alongside others[54-56]. For example, supply-side measures could offer substantial environmental benefits in India, such as tackling food loss[57 58], closing yield gaps[59 60] improving efficiency of livestock production[61 62], and wider adoption of multiple cropping. Much of the sustainable diets literatures focuses on HICs and associated GHG emissions of dietary change, though for some LMICs such as India, water and land use pressures may be particularly urgent[63-65]. For example, cultivatable land in India has decreased in recent decades, and with competing demands for land, there is little room to increase agricultural land area[66]. Given that achieving healthy diets for undernourished individuals would result in additional pressures on agricultural production, the importance of these other agricultural improvements is of high priority – and implementing them could more than offset the environmental pressures of providing healthy diets nationally. The urgency of implementing these solutions will also likely increase in the near term, as environmental change is projected to exacerbate dietary and environmental challenges by lowering yields and nutritional quality of crops[67-69].

The lesson from most countries globally is that economic development does not necessarily result in consumption of a healthy diet[28 45]; rising incomes may shift people from undernutrition, but introduce NCD risks, such as those due to excess dietary energy, sugar, oils, and salt. We have shown that a simplified scenario of this trajectory in India would also result in substantially increased environmental footprints. This trajectory may not be inevitable, as the example of South Korea shows, where incomes have grown rapidly while obesity and other NCDs have remained relatively low[28]. Navigating the dual burden of malnutrition will, however, require marked efforts to implement a comprehensive and coordinated suite of policies across the food system, for example, in improved production, distribution and storage of nutrient-rich crops, subsidies and taxes for relevant foods, education on healthy diets, and regulating advertising and content of processed food.

Our study has several limitations. The analysis uses hypothetical scenarios, and should be interpreted as indicative of broad opportunities and challenges, rather than as projections. The shifts to various scenarios did not include other potential drivers such as trade or environmental pressures on food production that may affect the availability or affordability of food, and therefore the makeup of the dietary scenarios. Similarly, we were unable to model dynamically how dietary environmental footprints may fluctuate in response to changing intakes and associated agricultural production. We used average national values of environmental footprints. While the analysis could be improved with the use of more granular footprint data, where available, incorporating these would require more detailed knowledge than is currently available on the regional source of food groups consumed in any given state. We also did not include future projections of population, though this more clearly highlights the challenges of addressing the dietary gaps between current intakes and healthy diets. The underlying environmental data used proxies for some food items, as detailed environmental data for all foods eaten are not available, and are rare even for HICs. However, much of the literature attributing environmental impacts to diets uses similar methodology, and previous work has shown that using simplified food groups as proxies is a valid approach[70 71]. We had also assumed that all food in our dietary scenarios is domestically produced (this is true for the majority of food consumed in India[40]), and using this approach allowed us to gauge the total environmental impacts, though future analyses can be improved by combining international and intra-national trade data. The NSS dietary data recorded the expenditure on meals outside of the home, from which we estimated food group intake. However, the food groups eaten outside the home may be different from those which are recorded as purchased for the household, and the out-of-home data may underestimate total intake[32]. Micronutrient deficiencies remain a substantial challenge in India[72], though adherence to micronutrient RDAs in the optimised healthy diet would be difficult to reliably assess with the use of household expenditure data. We used the high-level, public-facing recommendations from the NIN[42] on macronutrients (energy, protein, and fats), and adequate fruit and vegetable intake, which match those of WHO/FAO[43]. We have assumed that meeting these intakes would provide a realistic and transparent healthy diet scenario, though our modelling may have assigned some individual-level intakes as healthy without fully aligning with additional micronutrient requirements. Affordability is an important consideration in the feasibility of shifting to healthy diets. We have not assessed the cost of our dietary shifts, though as the dietary guidelines we model are based on existing recommendations, we focused on the environmental impacts of achieving these public health goals. The expenditure data itself may not represent actual intakes, and substantial variation in dietary intakes was found in a comparison of dietary datasets in India, with particular discrepancies for nutrient-dense foods such as fruit and animal-based products[32]. However, under- or over-estimates of intake may have, to some extent, been cancelled out in the affluent diet scenarios, as for example, both baseline and scenario diets would likely include the same direction of measurement error. Also, we were not able to provide measures of error across the environmental footprints, as these are unavailable for the LU data, and inputs to generate uncertainty are not consistent across the WF and GHG data, which would produce incomparable uncertainty ranges. We are not aware of any other studies that have generated uncertainty ranges across several environmental indicators, and the methodology in this area remains a topic for further work. Additionally, the artificially narrow confidence intervals in the large national dietary data would not accurately represent true uncertainty ranges of intake. One of the strengths of our study is using a variety of environmental indicators, though a more comprehensive assessment could include additional outcomes for which data were not available to us, such as biodiversity and nutrient flows.

Future work is necessary to add finer detail to the environmental data, and understand implications at smaller spatial scales by, for example, using sub-national data on trade, production location, and environmental impacts with greater resolution, as pressures such as water stress vary considerably by region. In addition, interdisciplinary research will be vital to better understand the complex linkages between environment, food, and health[73].

India suffers a dual burden of malnutrition. Widespread adoption of healthy diets could generate substantial public health benefits through reducing hunger and nutrient deficiencies, and reducing risks of diet-related NCDs such as diabetes and hypertension. However, unlike in HICs, our study has demonstrated that widespread adoption of healthy diets may not reduce environmental footprints of the Indian food system relative to the status quo, albeit preferable to the widespread adoption of diets currently consumed by the wealthiest quartile of the population. Thus, to achieve improved population health and reduced environmental impacts, additional strategies to reduce food waste and increase the efficiency of food production will be required.

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LA designed the study in discussion with RG and AH, as part of his doctoral thesis. LA analysed the data and drafted the paper. EJMJ, FH, SV and JH contributed environmental footprint data. All authors were involved in critical revisions of the paper, and approved the final version. LA had final responsibility for the decision to submit for publication.

Conflict of interest

The authors declare no conflicts of interest.

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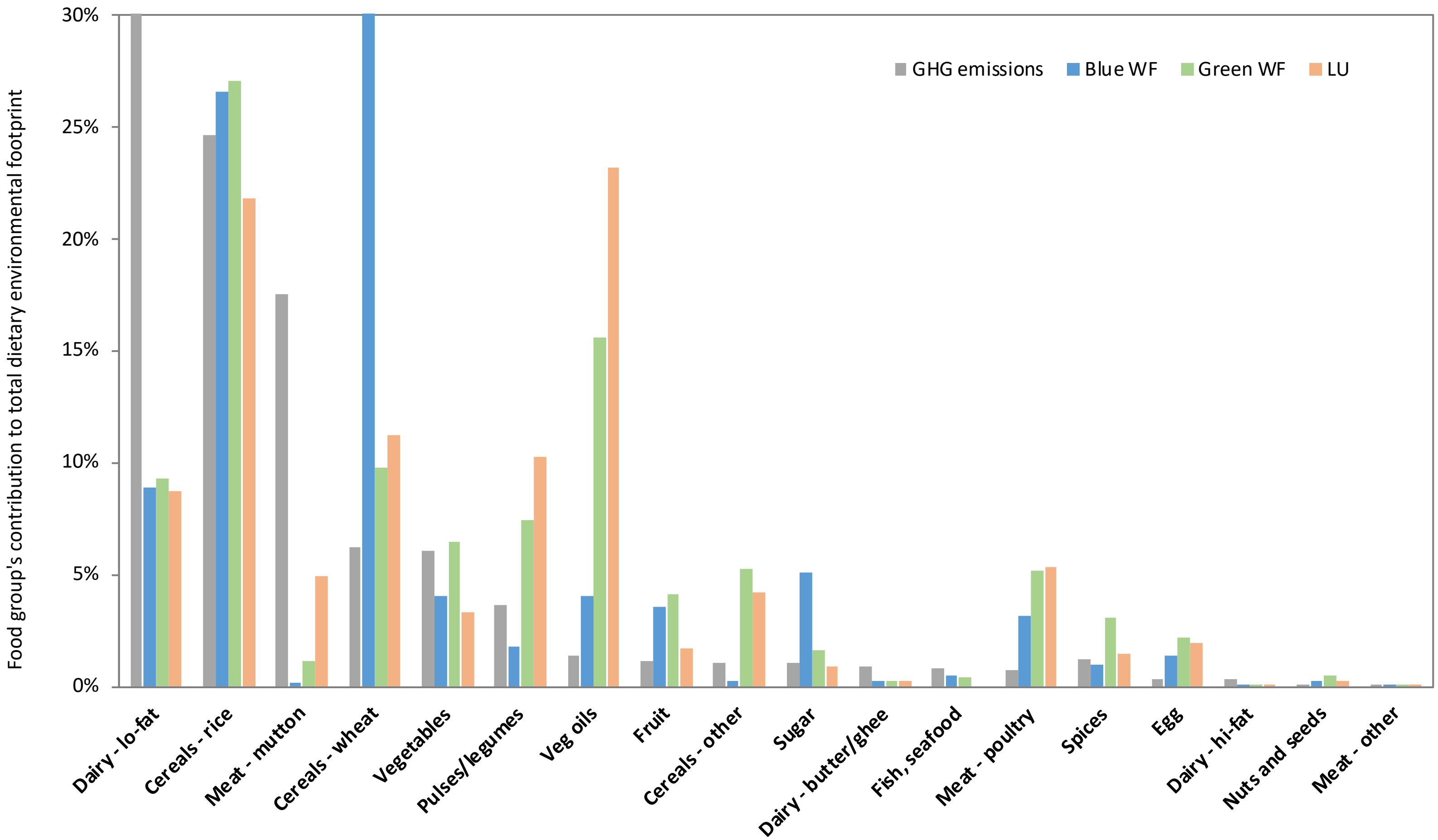
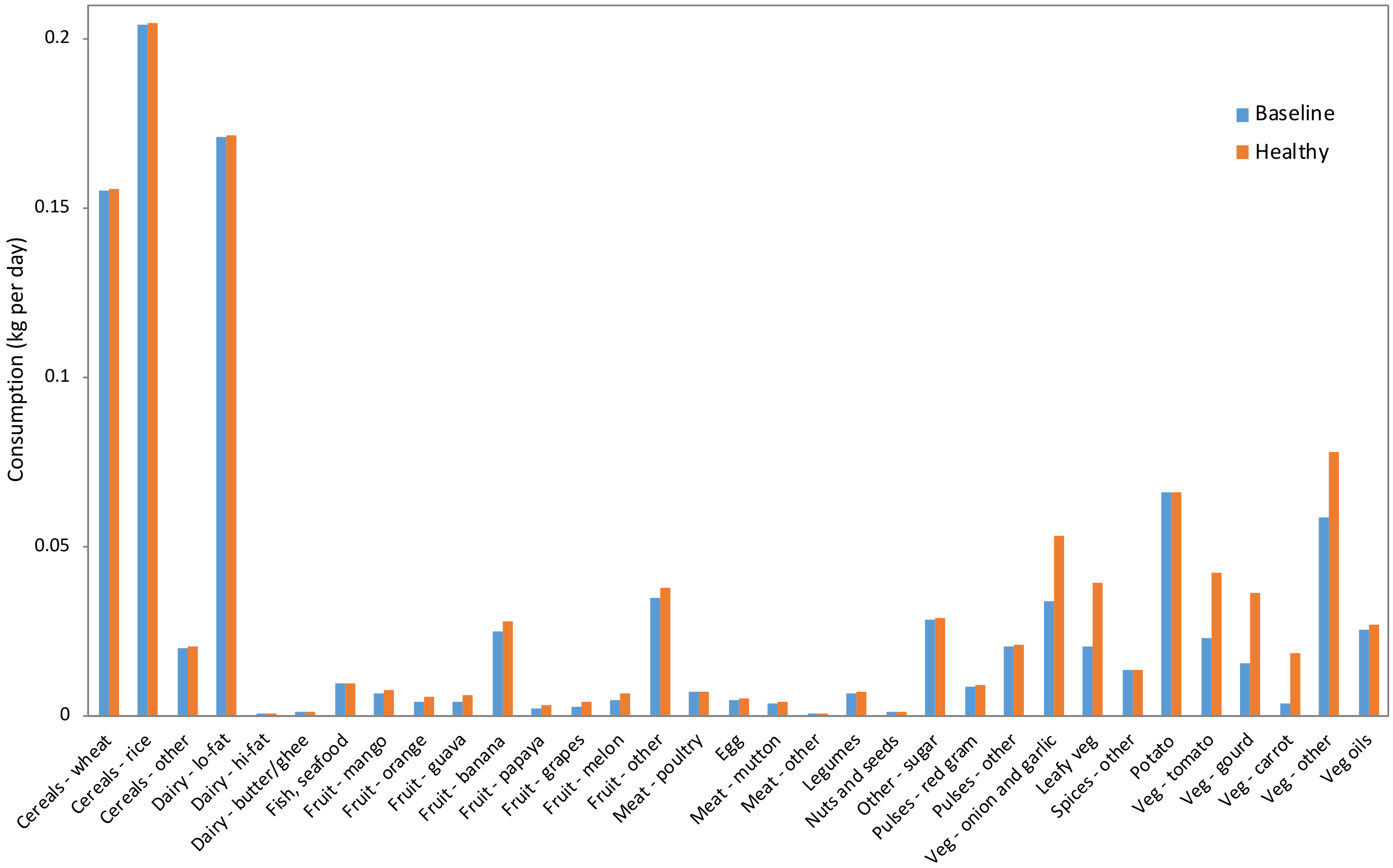
Supplementary figure 1: Contribution of food groups to total dietary greenhouse gas (GHG) emissions, blue and green water footprints (WFs), and land use (LU).

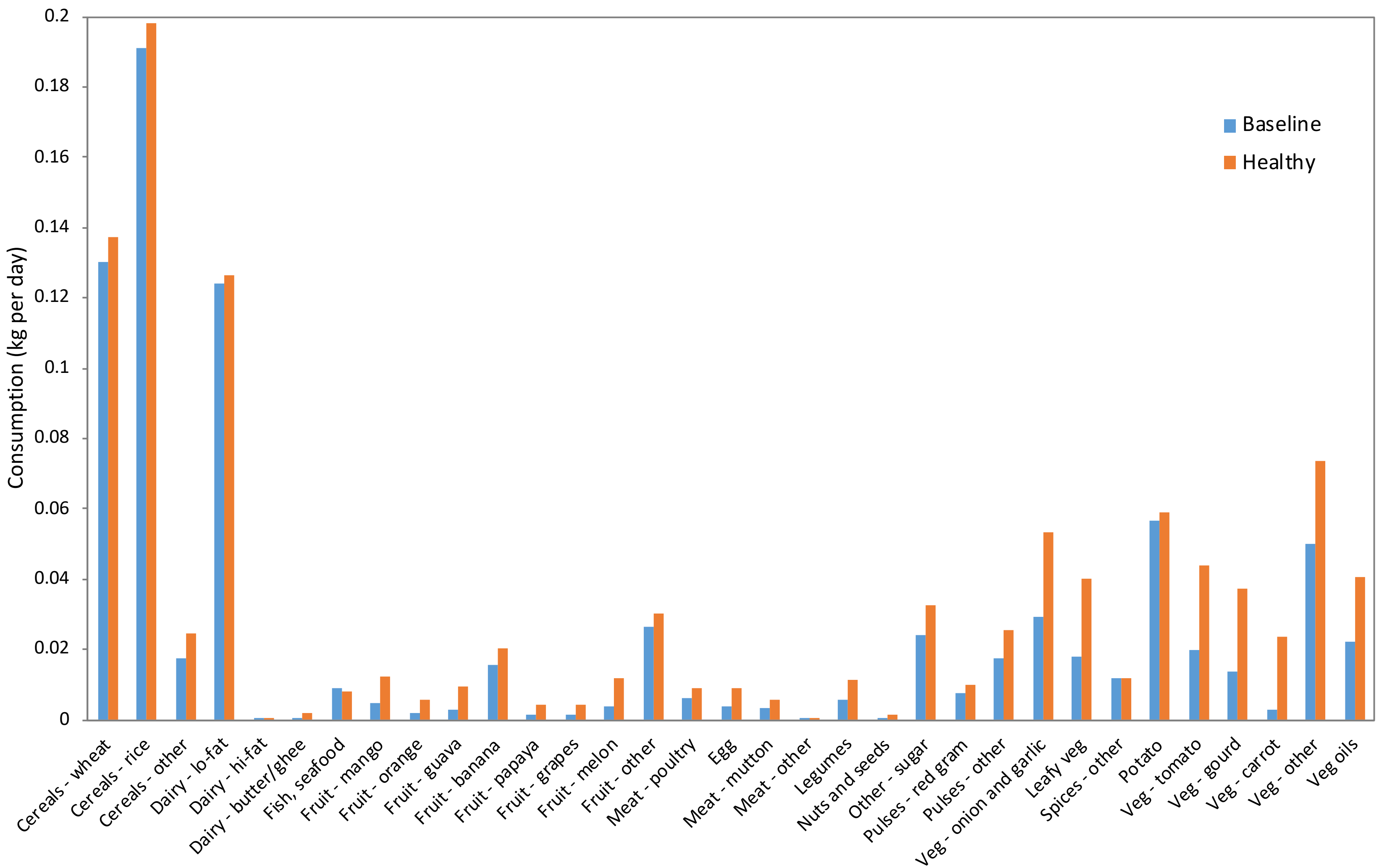


Note: GHG emissions from the dairy lo-fat category are 32%, and blue WF of the wheat category is 39%.

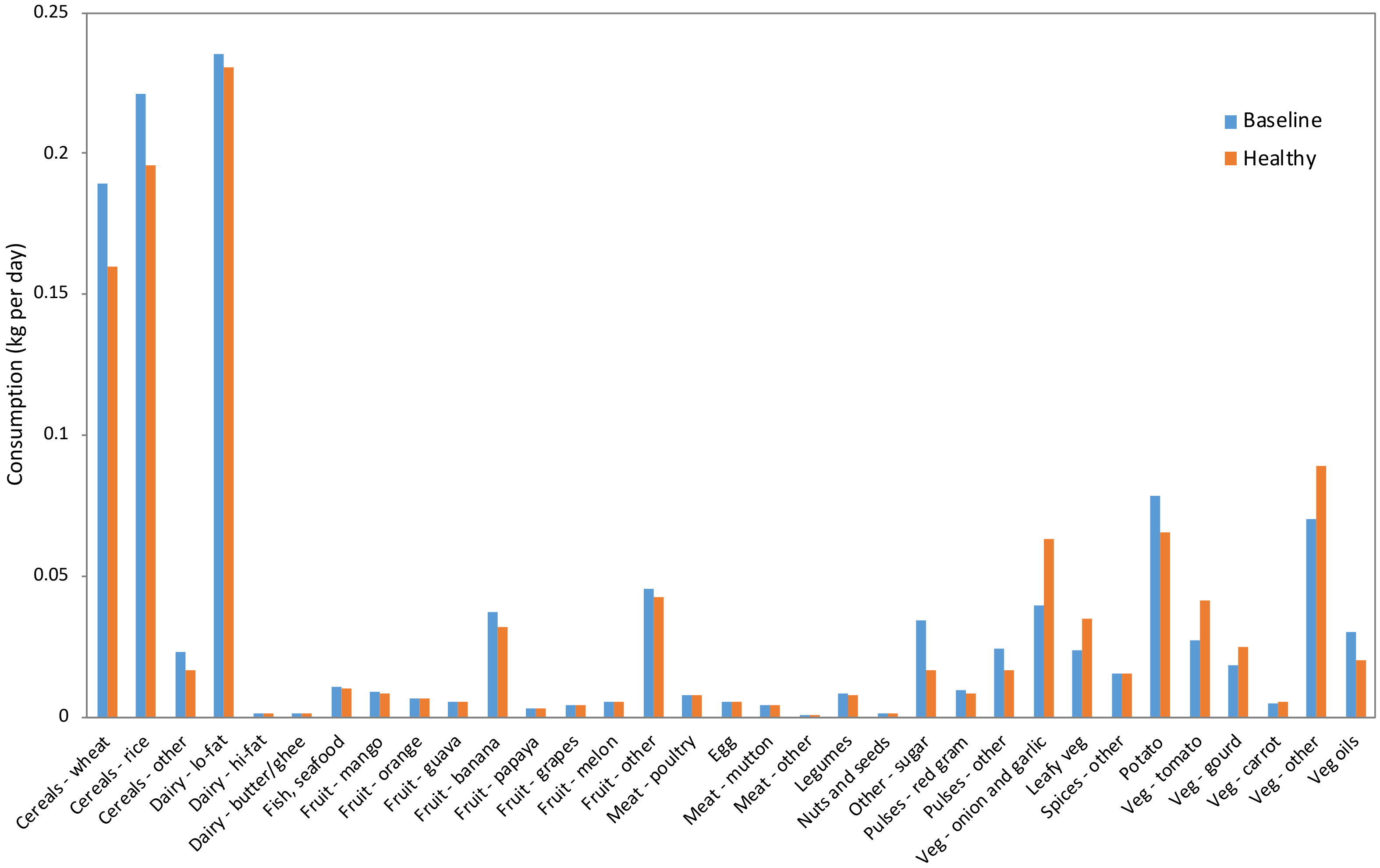
Supplementary figure 2: Intake of food groups in current average diets and optimised healthy diets, nationally.



Supplementary figure 3: Intake of food groups in current average diets and optimised healthy diets among those estimated to be below recommended dietary energy intake, nationally.



Supplementary figure 4: Intake of food groups in current average diets and optimised healthy diets among those estimated to be above recommended dietary energy intake, nationally.



Supplementary table 1: Allocation of individual food items to food groups.

Food group	Original food item
Cereals - wheat	wheat/atta
	maida
	suji, rawa
	sewai, noodles
	bread bakery
	other wheat products
Cereals - rice	rice
	chira
	khoi, lawa
	muri
	other rice products
Cereals - other	jowar & products
	bajra & products
	maize & products
	barley & products
	small millets &products
	ragi & products
	other cereals
Dairy - lo-fat	milk liquid
	baby food
	milk condensed/ powder
	curd
Dairy - hi-fat	ice-cream
	other milk products
Dairy - butter/ghee	ghee
	butter
Fish, seafood	fish, prawn
Fruit - mango	mango
Fruit - orange	orange, mausami
Fruit - guava	guava
Fruit - banana	banana
Fruit - papaya	papaya
Fruit - grapes	grapes
Fruit - melon	watermelon
	kharbooza
Fruit - other	jackfruit
	pineapple
	coconut
	green coconut
	singara
	pears/nashpati
	berries
	leechi
	apple
	other fresh fruits
	lemon
	dates
	raisin, kishmish, monacca,etc.

	coconut copra
	other dry fruits
Meat - poultry	chicken
Egg	eggs
Meat - mutton	goat meat/mutton
	beef/ buffalo meat
Meat - other	pork
	others birds, crab,oyster, tortoise, etc.
Legumes	beans, barbati
	groundnut
Nuts and seeds	cashewnut
	walnut
	other nuts
Sugar	sugar
	gur
	candy, misri
	honey
Pulses - red gram	arhar, tur
Pulses - other	gram split
	gram whole
	moong
	masur
	urd
	peas
	khesari
	other pulses
	gram products
	besan
	other pulse products
Veg - onion and garlic	onion
	garlic
Leafy veg	palak/other leafy vegetables
Spices - other	ginger
	jeera
	dhania
	turmeric
	black pepper
	dry chillies
	tamarind
	curry powder
	oilseeds
	other spices
Potato	potato
Veg - tomato	tomato
Veg - gourd	parwal/patal, kundru
	gourd, pumpkin
Veg - carrot	carrot
Veg - other	brinjal
	radish
	green chillies
	lady's finger

	cauliflower
	cabbage
	peas
	other vegetables
Veg oils	edible vegetable oils (mustard, groundnut, coconut, sunflower, soyabean, saffola, others)
	vanaspati, margarine

Supplementary table 2: Environmental footprints of food groups.

Food group	GHG emissions ($kgCO_2$-eq/kg food)	Green WF (m^3/kg food)	Blue WF (m^3/kg food)	Land use (m^2/kg food)
Cereals - wheat	0.540	0.985	1.366	2.867
Cereals - rice	1.614	2.072	0.715	4.227
Cereals - other	0.725	4.171	0.066	8.468
Dairy - lo-fat	2.524	0.845	0.285	2.016
Dairy - hi-fat	6.851	2.718	0.917	4.732
Dairy - butter/ghee	12.531	4.321	1.458	10.268
Fish, seafood	1.172	0.670	0.295	-
Fruit - mango	0.115	1.237	0.566	1.517
Fruit - orange	0.264	0.678	0.003	1.010
Fruit - guava	0.117	1.237	0.566	1.606
Fruit - banana	0.195	0.266	0.193	0.338
Fruit - papaya	0.117	0.267	0.087	0.278
Fruit - grapes	0.586	0.289	0.336	0.510
Fruit - melon	0.610	0.265	0.025	0.559
Fruit - other	0.117	1.158	0.218	1.038
Meat - poultry	1.425	11.782	2.530	30.631
Egg	1.119	7.721	1.658	16.987
Meat - mutton	63.531	4.872	0.290	52.913
Meat - other	1.425	3.324	0.272	5.162
Legumes	1.759	1.606	0.129	4.869
Nuts and seeds	1.286	9.410	1.525	13.358
Other - sugar	0.504	0.925	0.995	1.294
Pulses - red gram	1.398	5.068	0.282	18.213
Pulses - other	1.261	3.114	0.323	10.814
Veg - onion and garlic	0.740	0.164	0.143	0.653
Leafy veg	0.155	0.412	0.046	0.466
Spices - other	1.254	3.626	0.424	4.521
Potato	0.497	0.218	0.038	0.565
Veg - tomato	0.138	0.223	0.043	0.523
Veg - gourd	0.212	0.375	0.012	1.301
Veg - carrot	0.703	0.082	0.060	0.724
Veg - other	0.201	1.059	0.217	0.466
Veg oils	0.746	9.541	0.867	35.868

Supplementary table 3: Daily energy, vegetable and fruit intake, according to national dietary guidelines[42].

Sex	Age (years)	Energy (kcal/*capita*/day)	Vegetable intake (g/*capita*/day)	Fruit intake (g/*capita*/day)
Male	<1	584	55	55
	1-3	1060	100	100
	4-6	1350	150	100
	7-9	1690	200	100
	10-12	2190	300	100
	13-15	2750	300	100
	16-17	3020	300	100
	18-59	2730	300	100
	60-69	2184	240	80
	70+	1911	210	70
Female	<1	584	55	55
	1-3	1060	100	100
	4-6	1350	150	100
	7-9	1690	200	100
	10-12	2010	300	100
	13-15	2330	300	100
	16-17	2440	300	100
	18-59	2230	300	100
	60-69	1625	240	80
	70+	1593	210	70

Supplementary table 4: Relative changes in greenhouse gas (GHG) emissions, water footprints (WFs) and land use (LU) from shifting average Indian diets to healthy guidelines and affluent dietary scenarios.

	GHG emissions					Blue WF					Green WF					LU				
Region	Baseline	Healthy		Affluent		Baseline	Healthy		Affluent		Baseline	Healthy		Affluent		Baseline	Healthy		Affluent	
	$kgCO_2$-eq	$kgCO_2$-eq	% diff.	$kgCO_2$-eq	% diff.	m^3	m^3	% diff.	m^3	% diff.	m^3	m^3	% diff.	m^3	% diff.	m^2	m^2	% diff.	m^2	% diff.
North rural ARI	2.1	1.95	-6.7			0.8	0.7	-13.4			1.7	1.5	-16.1			4.5	3.6	-20.0		
North rural BRI	1.3	1.5	12.2			0.6	0.6	11.6			1.2	1.6	26.7			3.3	4.2	28.2		
North rural	1.8	1.8	-0.7	2.5	38.5	0.7	0.7	-3.1	0.8	18.1	1.5	1.4	-8.0	1.9	22.5	4.0	3.5	-13.5	4.8	19.8
North urban ARI	2.0	1.9	-5.0			0.8	0.7	-11.4			1.9	1.6	-16.2			4.9	3.9	-20.0		
North urban BRI	1.2	1.4	16.1			0.5	0.6	14.6			1.3	1.6	28.7			3.3	4.4	31.8		
North urban	1.6	1.6	1.6	2.2	40.1	0.6	0.6	1.0	0.8	23.2	1.5	1.6	1.4	2.1	34.5	4.0	4.0	0.7	5.2	29.3
North total	**1.7**	**1.7**	**-1.5**	**2.4**	**39.1**	**0.7**	**0.7**	**-1.4**	**0.8**	**20.0**	**1.5**	**1.5**	**-4.9**	**2.0**	**27.2**	**4.0**	**3.7**	**-7.9**	**5.0**	**23.5**
North-east rural ARI	1.6	1.4	-12.6			0.6	0.5	-15.7			2.0	1.8	-6.3			4.6	4.4	-3.2		
North-east rural BRI	1.2	1.4	16.1			0.4	0.5	20.2			1.4	1.8	31.6			3.3	4.6	39.6		
North-east rural	1.4	1.4	-0.3	1.8	29.4	0.5	0.5	5.4	0.5	18.9	1.6	1.8	15.6	2.0	24.5	3.7	4.5	19.7	4.7	27.5
North-east urban ARI	1.7	1.6	-8.1			0.6	0.5	-14.0			2.1	1.9	-8.1			5.0	4.5	-8.6		
North-east urban BRI	1.2	1.5	28.7			0.4	0.5	25.5			1.4	2.0	39.6			3.4	5.1	49.6		
North-east urban	1.3	1.5	13.0	1.8	34.3	0.5	0.5	9.7	0.6	24.6	1.6	1.9	15.5	2.1	27.9	3.9	4.6	19.5	5.1	31.2
North east total	**1.4**	**1.4**	**3.1**	**1.8**	**30.1**	**0.5**	**0.5**	**6.4**	**0.5**	**19.7**	**1.6**	**1.8**	**15.8**	**2.0**	**25.0**	**3.7**	**4.5**	**20.3**	**4.8**	**28.0**
East rural ARI	1.5	1.3	-11.3			0.6	0.5	-14.5			1.7	1.7	-3.5			4.2	4.3	1.8		
East rural BRI	1.0	1.1	11.6			0.5	0.5	17.7			1.3	1.7	30.4			3.1	4.2	35.7		
East rural	1.2	1.2	1.3	1.6	35.0	0.5	0.5	-1.5	0.6	14.9	1.5	1.6	11.2	1.8	20.6	3.6	4.1	13.9	4.5	25.7
East urban ARI	1.6	1.5	-5.8			0.6	0.6	-11.8			1.9	1.7	-10.6			4.8	4.2	-12.5		
East urban BRI	1.3	1.7	34.2			0.5	0.6	20.9			1.4	1.9	38.7			3.5	5.2	48.3		
East urban	1.4	1.5	9.6	1.7	23.3	0.5	0.6	6.7	0.6	18.5	1.5	1.7	11.9	2.0	27.3	4.0	4.5	14.3	5.0	25.4
East total	**1.2**	**1.2**	**-2.3**	**1.7**	**32.6**	**0.5**	**0.5**	**1.3**	**0.6**	**15.6**	**1.5**	**1.6**	**7.6**	**1.8**	**21.9**	**3.7**	**4.0**	**8.0**	**4.6**	**25.6**
South rural ARI	1.8	1.7	-5.5			0.6	0.5	-12.0			2.3	2.0	-12.7			5.6	4.7	-15.5		
South rural BRI	1.2	1.4	18.4			0.4	0.5	19.6			1.6	2.1	31.0			3.9	5.4	39.6		
South rural	1.4	1.6	8.1	2.0	37.8	0.5	0.5	6.0	0.6	21.9	1.9	2.0	8.0	2.2	19.8	4.5	4.9	9.1	5.5	22.1
South urban ARI	2.0	2.0	-3.9			0.6	0.6	-11.4			2.4	2.0	-12.9			5.7	4.8	-16.3		
South urban BRI	1.3	1.6	18.3			0.4	0.5	19.2			1.6	2.1	30.3			4.0	5.5	38.2		

South urban	1.6	1.7	6.1	2.2	37.9	0.5	0.5	7.0	0.6	25.2	1.9	2.1	9.4	2.3	23.4	4.6	5.1	9.2	5.7	22.5
South total	**1.5**	**1.6**	**6.4**	**2.1**	**37.8**	**0.5**	**0.5**	**5.8**	**0.6**	**23.2**	**1.9**	**2.0**	**8.2**	**2.3**	**21.1**	**4.5**	**5.0**	**9.5**	**5.6**	**22.2**
West rural ARI	1.3	1.3	-2.6			0.6	0.5	-8.1			2.0	1.7	-13.9			5.1	4.1	-19.3		
West rural BRI	1.0	1.1	18.2			0.4	0.5	18.8			1.5	1.9	31.0			3.8	5.1	34.6		
West rural	1.1	1.2	7.2	1.5	32.8	0.5	0.5	7.2	0.6	19.7	1.7	1.8	10.2	1.9	16.6	4.3	4.7	9.5	5.0	17.7
West urban ARI	1.8	1.8	-3.0			0.7	0.6	-8.4			2.1	1.8	-14.0			5.4	4.4	-19.0		
West urban BRI	1.2	1.7	43.2			0.5	0.6	21.0			1.5	2.0	33.7			3.9	5.4	36.5		
West urban	1.4	1.6	8.1	1.8	28.5	0.5	0.6	5.0	0.6	16.8	1.7	1.8	9.1	2.0	20.8	4.5	4.9	9.5	5.3	17.9
West total	**1.2**	**1.3**	**6.9**	**1.6**	**30.6**	**0.5**	**0.5**	**5.5**	**0.6**	**18.4**	**1.7**	**1.8**	**9.7**	**2.0**	**18.5**	**4.4**	**4.8**	**9.9**	**5.1**	**17.8**
Central rural ARI	1.4	1.3	-7.5			0.7	0.6	-12.4			1.6	1.4	-12.9			4.0	3.4	-15.8		
Central rural BRI	0.9	1.1	13.9			0.5	0.6	14.2			1.1	1.5	33.3			2.9	4.0	35.3		
Central rural	1.2	1.1	-2.1	1.7	42.5	0.6	0.6	0.9	0.7	18.1	1.3	1.3	1.7	1.6	22.4	3.5	3.4	-1.5	4.3	23.4
Central urban ARI	1.8	1.7	-4.2			0.7	0.7	-9.9			1.7	1.4	-14.5			4.5	3.7	-18.9		
Central urban BRI	1.2	1.5	31.4			0.5	0.6	16.1			1.1	1.6	36.4			3.2	4.4	38.1		
Central urban	1.4	1.5	6.2	1.9	31.7	0.6	0.6	3.7	0.7	16.8	1.4	1.5	7.5	1.7	27.8	3.8	4.0	6.7	4.6	23.0
Central total	**1.2**	**1.2**	**-0.2**	**1.7**	**39.7**	**0.6**	**0.6**	**1.9**	**0.7**	**17.8**	**1.3**	**1.4**	**2.7**	**1.7**	**23.6**	**3.5**	**3.5**	**-0.3**	**4.3**	**23.3**
India rural ARI	1.6	1.5	-6.5			0.6	0.6	-13.8			1.8	1.6	-11.4			4.5	3.9	-13.9		
India rural BRI	1.0	1.4	31.4			0.5	0.6	18.7			1.3	1.8	34.5			3.3	4.7	41.3		
India rural	**1.3**	**1.3**	**0.9**	**1.8**	**37.7**	**0.5**	**0.6**	**2.5**	**0.6**	**18.2**	**1.5**	**1.6**	**4.7**	**1.8**	**20.7**	**3.8**	**4.0**	**3.5**	**4.7**	**22.8**
India urban ARI	1.9	1.8	-4.3			0.7	0.6	-10.4			2.0	1.8	-12.4			5.1	4.2	-17.7		
India urban BRI	1.2	1.5	22.9			0.5	0.6	17.0			1.4	1.9	33.3			3.7	5.1	39.5		
India urban	**1.5**	**1.6**	**6.9**	**2.0**	**32.7**	**0.6**	**0.6**	**4.5**	**0.7**	**20.0**	**1.6**	**1.8**	**8.7**	**2.0**	**25.5**	**4.2**	**4.6**	**9.4**	**5.2**	**22.8**
India ARI	**1.6**	**1.6**	**-5.5**			**0.7**	**0.6**	**-12.8**			**1.8**	**1.6**	**-12.8**			**4.7**	**3.9**	**-15.6**		
India BRI	**1.1**	**1.4**	**27.8**			**0.5**	**0.6**	**18.4**			**1.4**	**1.8**	**33.9**			**3.4**	**4.8**	**40.5**		
India Total	**1.3**	**1.4**	**4.3**	**1.8**	**36.1**	**0.5**	**0.6**	**3.2**	**0.7**	**18.7**	**1.6**	**1.6**	**5.1**	**1.9**	**22.1**	**3.9**	**4.1**	**4.4**	**4.8**	**22.8**

Supplementary File 1: details on dietary adjustments and land use values.

Adjustments made to reported food purchase in National Sample Survey household consumer expenditure data

Dietary data were adjusted for high-income households that provide food to poorer households in exchange for labour or services as follows:

$$adjusted\ intake = \ C_i \left(\frac{M_h + M_f}{M_h + M_g} \right)$$

where C is the unadjusted intake of food item i, M_h is the number of meals consumed by the household members, M_f is the number of meals received free from other households by household members, and M_g is the number of meals consumer by non-members (guests, employees, etc.).

Data were additionally adjusted for foods eaten out of home. NSS records purchase of ~140 individual foods which we matched to nutritional composition data for our analysis. However, some of the recorded purchases are of a variety meals and snacks outside of home, which we were not able to break down into food groups required for our analysis, such as fruits and vegetables. To approximate intake of food groups from these meals and snacks, we used the NSS data on estimated caloric content of out of home meals. We took the proportion of these out of home calories out of all calories, and then scaled the individual food items purchase by this proportion. This adjustment assumed that the distribution of food groups in the meals purchased out of home was the same as the purchased food items.

Calculation of land use footprints

National-level yield data for crops were obtained from the FAO, available for the years 1961–2014 (Table 1; FAOSTAT, 2017). We used data for 2014. These data provide an estimate of the quantity of individual crop items produced per hectare and are principally derived from national agricultural surveys. Standard technical conversion factors (FAO, 1972) were applied to account for non-edible components (e.g. fruit skin; Table 1). For livestock products, FAOSTAT publish data on yields per head of livestock but they do not publish yields per unit area of land. Thus, yield data for livestock products were calculated as follows: (i) the make-up of feed (i.e. concentrates, grass and non-grass roughages) in grazing, mixed and industrial systems for different animals was derived from Mekonnen and Hoekstra (2012) and Harris et al. (2017; Table 2); (ii) the yield of concentrates was based on

FAOSTAT yield and feed production data for cereals, oil crops, and pulses (FAOSTAT, 2017); (iii) the yield of grass was assumed to be 4 kg ha^{-1} year^{-1} (Shankar & Gupta, 1992) and it was considered that production of roughage other than grass (i.e. by-products of other crops) do not require additional land; (iv) the land area required *per* kg of livestock product was calculated on the basis of feed yields and feed conversion efficiencies. This value was inverted to give kg of food product *per* ha of land. Nationally, <1% of feed is imported (FAOSTAT 2017) so it was assumed that all feed was grown in India. Land requirements of fish were not considered.

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RESEARCH PAPER COVER SHEET

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SECTION A – Student Details

Student ID Number	231894	**Title**	Mr
First Name(s)	Lukasz		
Surname/Family Name	Aleksandrowicz		
Thesis Title	Impact of dietary shifts in India on greenhouse gas emissions, land use, water use, and food expenditure: a nationally-representative study		
Primary Supervisor	Prof Sir Andy Haines		

If the Research Paper has previously been published please complete Section B, if not please move to Section C.

SECTION B – Paper already published

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Where is the work intended to be published?	Global Food Security
Please list the paper's authors in the intended authorship order:	Aleksandrowicz L, Green R, Cornelsen L, Haines A

Stage of publication	**Not yet submitted**

SECTION D – Multi-authored work

For multi-authored work, give full details of your role in the research included in the paper and in the preparation of the paper. (Attach a further sheet if necessary)	I designed the study, performed the analysis, and drafted the manuscript included in the thesis.

SECTION E

Student Signature	[redacted]
Date	Apr 2, 2019

Supervisor Signature	[redacted]
Date	2nd April 2019

The cost of eating a healthy and environmentally sustainable diet: an analysis of the 2011-2012 Indian National Sample Survey

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Abstract

Dietary choice is a major driver of environment change, and unhealthy diets are a leading risk factor for non-communicable disease. Shifting to healthier dietary patterns can offer environmental co-benefits. However, food cost may be a barrier to dietary change, as healthy diets are often more expensive than average diets in both high-income and low- and middle-income countries (LMICs). Little is known about how environmental considerations impact on the cost of healthy diets, particularly in the context of LMICs. We assessed the cost of household diets that were healthier and more sustainable, compared to average diets in India.

We used household food purchase data from the 2011-2012 Indian National Sample Survey to approximate dietary intake and cost. This was matched to Indian-specific data on dietary greenhouse gas (GHG) emissions, water footprints (WFs) and land use (LU). Mean environmental footprints and dietary costs were calculated for a range of diets: an Adequate reference diet (meeting minimum dietary energy requirements), a Healthy diet (meeting selected Indian dietary guidelines), a Relatively Healthy diet (similar to Healthy, with lower fruit and vegetable requirements at 3 servings/day), as well as lower footprint versions of these (lower GHG, LU and WU than mean Indian dietary footprints). Linear regression models tested for differences in cost between Adequate and Healthy and lower footprint diets, at the national level, as well as across quantiles of household expenditure, and by rural/urban residence.

Prevalence of healthy diets was low nationally (2 and 15% for Healthy and Relatively Healthy diets, respectively), and lower for the lower footprint versions of these (<1 and 7%, respectively). Adherence to individual healthy guideline components increased at higher expenditure quartiles. Regression models generally showed increases in cost between Adequate and improved diets (Relatively Healthy and Healthy diets, and the lower footprint versions of these). For the improved diets with lower footprints, the increased costs were greater among lower-income and rural households. Conversely, healthy and lower footprint diets were cheaper or had no difference in cost than adequate diets for high-income and urban households. Fruit and vegetables, and pulses, were seen to contribute most to the higher cost of the improved diets.

This is the first study, to our knowledge, to assess the cost of observed diets in relation to their healthiness and environmental sustainability, and an initial step in better understanding uptake barriers of improved diets. Given the higher costs of improved diets for many households in the country, efforts must be made to increase the affordability and accessibility of fruits and vegetables, among other nutrient-rich food groups, to improve both health and environmental sustainability in India.

Introduction

Dietary choice is a major driver of environment change. Agricultural production globally contributes about 20-30% of greenhouse gas (GHG) emissions, 70% of freshwater withdrawals, and uses one-third of ice-free land[1-3]. Unhealthy diets are one of the key risk factors of non-communicable disease, and a leading contributor to the global burden of disease[4,5]. Studies have shown that adoption of healthy diets in high-income countries (HICs) can have environmental co-benefits[6,7]. A range of healthy and environmentally sustainable dietary patterns have been assessed in the literature, including following national dietary guidelines. However, affordability may be a barrier to widespread adoption of healthy and sustainable diets[8], particularly in low and middle-income countries (LMICs) where a relatively high share of income is spent on food[9].

The literature to date has highlighted that healthier diets and food items tend to be more expensive than less healthy versions[10-12], though with exceptions in some cases[13-15], where healthier diets contain less dietary energy and therefore require less overall spend on food. However, less is known about the dietary cost implications of combining health and environmental sustainability considerations. Few studies have assessed the costs of both healthy and environmentally sustainable diets, and the preliminary evidence remains mixed. Studies using mathematical optimisation approaches find that it is possible to model a healthy and environmentally sustainable diet that is either cheaper or cost-neutral, compared to average diets[16-19]. However, studies using observed diets have found that self-selected healthier and more environmentally sustainable diets are more expensive[20-

[23], as well as less expensive[24-26]. It is not yet fully clear what drives the differences in results across studies. Furthermore, only one study to date in this area has focused on a LMIC[16], and has used an optimisation approach.

India is home to about one-fifth of the global population, and faces substantial nutritional challenges, including high rates of undernutrition alongside increasing rates of obesity and non-communicable diseases (NCDs) among populations at all income levels[27-29]. Increasing urbanization and growing incomes have resulted in Indian diets transitioning away from staple foods, such as pulses and coarse cereals, to vegetable- and animal-based fats, and energy-dense, processed foods[30-32]. As incomes continue to rise, higher discretionary spending on food is projected to diversify the nutritional content of diets, as well as promote excess dietary energy intake[33]. Conversely, for low-income individuals, access and affordability of adequate dietary energy, as well as dietary diversity, remains a challenge[34].

India is also facing substantial environmental pressures due to agriculture, consequently placing further challenges on its ability to produce food. Greenhouse gas (GHG) emissions per capita in India currently remain low compared to HICs, but agricultural irrigation accounts for 90% of freshwater use, with depleting groundwater reserves in some regions[35]. Furthermore, despite India's large share of the global population, the country covers just over 2% of the world's land, and has little capacity to increase agricultural production area, due to competing demands for land[36]. We have recently shown that a scenario of adoption of healthy diets nationally may slightly increase environmental footprints, due to the important goal of bringing a large number of undernourished people up to adequate dietary energy and sufficient fruit and vegetable intake[37]. However, for a significant portion of the population – those who already consume sufficient dietary energy – a shift to healthy diets could decrease environmental footprints. Little is known about the cost and feasibility of such shifts in LMICs, and no studies to date have characterised the costs of observed diets in relation to their healthiness and environmental sustainability in India, or other LMICs.

In this study, we combine nationally-representative food expenditure data with food-specific GHG emissions, water footprints (WFs), and land use (LU), to explore the relationships between cost, healthiness and environmental sustainability of observed household-level diets. More specifically, this study assesses the questions: how many households currently consume healthy and environmentally sustainable diets; what are their costs in relation to current average diets; and which foods contribute to the difference in cost?

Methods

Data

Dietary and food expenditure data were derived from the 68th round of the Indian National Sample Survey (NSS), a nationally-representative household expenditure survey conducted in 2011-2012 (n=101,651 households)[38]. The NSS questionnaire records the quantity and value of approximately 140 food, meal and beverage items purchased by households within the last month. As data for actual intake of foods at this level of detail and scope of sample do not exist[39], we used the quantity of food purchased as a proxy for intake. We used the improved “type 2” format of the survey which used 7-day recall for meats, eggs, oils, fruits and vegetables, and 30-day recall for cereals, pulses and sugar (relative to the “type 1” format, which retains 30-day recall for all food groups). The survey was conducted over four seasonal sub-rounds within the survey year, with each sub-round consisting of a nationally-representative sample of approximately equal size.

We adjusted household intake for meals received by members (school meals, payment for labour, and others), and/or served to non-household members (further details in Supplementary file 1). These are recorded separately from the food expenditure and would otherwise skew the amount of food available for household consumption from the recorded expenditure. We calculated households’ total dietary energy (kcal), protein (g) and fat (g) intake using the macronutrient composition data provided by NSS documentation, for each of the 137 food items, and aggregated the intake of these items into 34 food groups based on nutritional content similarity. Households with per capita dietary energy intakes below 200 or above 5000 kcal/day were excluded as outliers (n=519), and our final sample of households was 100,338. To approximate food group intake from meals eaten out of home, we scaled up the quantity of intake of the 34 food groups by the proportion of dietary energy derived from out of home meals and snacks (additional details in Supplementary file 1). We then linked each food group to estimates of GHG emissions, blue and green WFs, and LU associated with the production of food items.

We used existing data on GHG emissions (kg CO_2-eq/kg food product) from the literature[40,41]. Data for the majority of foods group in our analysis (22 out of 34) were taken from a study using the Cool Farm Tool (CFT) to estimate emissions of agricultural production of major Indian crops and livestock products[41]. For groups that could not be assessed as above, production stage emissions were derived from the published literature, or a CFT-derived proxy was allocated[40]. Production stage emissions were then combined with post-production stage emissions, also based on a review of the published literature. Where two or more items were aggregated within a food group (i.e., other pulses, other cereals, ruminant meats, etc.), footprints were weighted by the relative quantity of the individual items consumed.

Data on India-specific WFs (L/kg food product) were used from a previous study that derived footprints for the same food groups and items used in this analysis[42]. The existing values were adapted from a publicly-available database from the Water Footprint Network (WFN)[43,44]. Individual product footprints from the WFN data were matched to food groups based on author judgement, and the total footprint of a food group was weighted by the quantity of consumption of individual items within the group. We combined blue (ground and surface) and green (rainfall) WFs in our overall WF indicator.

Land use (m^2/kg food product) values for Indian crops and livestock were taken from a previous analysis[37]. In brief, land use for crops was derived directly from FAO yield data for India for the year 2014[45]. FAO data for items were matched to food groups based on author judgement. Yield data for livestock products were calculated on the basis of livestock feed requirements[44], yields of feed crops and fodder[45,46], and feed conversion efficiencies. Less than 1% of feed is imported in India[45], so it was assumed that all feed was grown in the country.

Further details have been published elsewhere on the data for GHG emissions[40,41], WFs[42], and LU[37], as well as details on the groupings of items into food groups[37]. Food group-specific footprint values used in the analysis are provided in Supplementary table 1.

Measuring healthiness of household-level intake

To measure the healthiness of diets, we compared household-level intake to selected dietary guidelines from the NIN[47], including recommendations on dietary energy, fruit, and vegetable intake, and % of dietary energy derive from protein and fat. Recommendations for % energy from protein and fat were 10-15 and 20-30%, respectively, and recommendations for each household for dietary energy, fruit, and vegetable intake varied depending on the age and sex composition of the household (these requirements are shown in Supplementary table 2). A healthy dietary energy intake for a household was taken as the total observed dietary energy falling within the summed individual-level recommendations for low and high physical activity levels for household members (a worked example is shown in Supplementary table 3). Fruit and vegetable intake at the household level was considered healthy if it reached at least the summed recommended age- and sex-specific intake for each household member.

Dietary categories

To understand differences in dietary costs across varying degrees of healthiness and environmental sustainability, we grouped households into five constructed dietary categories; an Adequate average reference diet, two diets with health considerations (a Relatively Healthy diet, and a Healthy diet), as well as lower environmental footprint versions of each of the two health-oriented diets. These are further explained below, and summarised in Table 1.

Adequate diet: we included all households estimated to consume at least the minimum recommended dietary energy for each household member (assuming low physical activity) as the baseline group. Using an average diet of the total Indian population as a baseline would have included households facing poverty and undernutrition; households in this context would experience substantial barriers to improving diets, and would be a less appropriate reference group than those that have attained at least dietary energy sufficiency, and who may have relatively more capacity to change dietary patterns.

Healthy diet: households in this category met criteria for a healthy diet according to the selected dietary guidelines described in the section above.

Relatively Healthy diet: given the low prevalence of households meeting the fully guideline-adherent Healthy diets, we constructed an intermediary category which does not meet all NIN guidelines, but is healthier than the reference (Adequate) diet. We assessed the population per capita median values of each of the dietary guideline components (e.g. median number of grams of vegetable intake per day), and in cases where the median was not within dietary guidelines, we relaxed that guideline to the median value. Our resulting guidelines for the Relatively Healthy diet did not change for dietary energy range or proportion of dietary energy from protein; the target range of proportion of dietary energy from fat was widened slightly to 19.5-30% (from an original lower guideline of 20%); and combined intake of fruit and vegetables was lowered to 240 g/day (sample median 229g, which we rounded up to correspond to an intuitive measure of 3 servings). This latter guideline is also in line with recent work showing that much of the health gains from eating fruit and vegetables are realised at about 3 servings per day, compared to those who have no consumption[48]. However, studies have also shown that benefits can accrue for health at up to five[48], six[49], or ten[50] servings per day.

To identify households with lower than average diet-related environmental footprints, we first calculated mean footprints for GHG emissions (kgCO_2-eq), WFs (m^3), and LU (m^2) by state and dietary energy status (whether a household met the minimum recommended dietary energy intake across household members). Footprints are in large part a function of absolute dietary energy intake, and we therefore chose to derive several sub-sample footprint means, rather than a single population mean. Households whose dietary footprints were all below the mean footprints in their respective demographic grouping were classified as lower footprint (LF), using a similar binary approach to compare relative footprints as Masset et al.[24]

For conciseness, and where appropriate, the four dietary categories with environmental and/or health considerations are variously referred to as 'improved diets' when comparing to the Adequate reference diet.

Analysis

We assessed dietary costs using a variety of comparisons across dietary categories and sub-samples. We first tested the difference in cost at the national level, between diets with health considerations against the Adequate diet, and then diets with both health and environmental considerations against the Adequate diet. We then directly compared costs between diets with health considerations only, versus those with both health and environmental sustainability considerations (rather than against Adequate diets). We further investigated in more detail the cost of healthy and lower footprint diets among population sub-samples defined by quartiles of monthly per capita expenditure (MPCE, taken as a proxy for wealth), and rural or urban residence. Lastly, we also assessed which food groups contributed to the difference in overall cost of the healthy and lower footprint dietary categories.

We tested the above by using linear regression models, where diet type was the key independent variable of interest, with the Adequate diet as the reference category. We adjusted the models for region (according to 6 Indian geographical regions), rural or urban residence, household size, dietary energy intake, and MPCE. A separate analysis of dietary costs stratified by MPCE quartiles, and by rural or urban residence, was also conducted. Household size was converted to log scale as it was not normally distributed. For the food group expenditure analysis, we ran these models using food group expenditure as the dependent variable, separately for cereals, oils and butter, pulses, fruit, vegetables, dairy, meat, and eggs. These models were additionally adjusted for the price paid per kg of each food group.

All calculations were performed using STATA 13.0.

Results

Proportion of population among healthy and environmentally sustainable dietary categories

The analysis included a sample of 100,338 households, 41% of who lived in urban and 59% in rural areas. The average household size was 4.6 individuals, and was lower in households with improved diets versus those with Adequate diets. Adherence to the Healthy diet among households was low at the national level: 2.4% among those estimated to consume the minimum recommended dietary energy. Adherence in urban areas was much higher than in rural areas (3.8% vs 1.5%, respectively), and increased for wealthier households (0.2%, 1.0%, 2.5% and 4.5%, across quartiles of MPCE, respectively). Sample size by dietary category and descriptive characteristics are summarised in Tables 2 and 3.

We also assessed adherence to each of the five dietary components used in our categorisation of a healthy diet (dietary energy range, proportion of calories from fat and protein, and intake of fruits and vegetables). Adherence was highest for the percentage of dietary energy from protein guideline (70% of the population), followed by dietary energy intake (57%), percentage of dietary energy from fat (39%), fruit intake (31%), and lowest for vegetable intake (22%). Adherence to each of the five components increased among higher MPCE quartiles; for example, the proportion of households in the first and fourth quartiles consuming within dietary energy guidelines was 44 vs. 58%, and the proportion meeting recommended fruit intake was 10 and 57%, respectively (Table 4).

The proportion of households eating a Relatively Healthy diet was 15.2% (12.5 and 19.4% for rural and urban areas, respectively), among those who already consumed at least the minimum dietary energy requirements (Table 2).

The proportion of households consuming Healthy diets and having lower than average environmental footprints was very low, at just 0.8% (0.5 and 1.2% by rural and urban regions, respectively). Comparatively, 7.0% of households attained a Relatively Healthy diet with lower footprints (5.9 and 8.7% among rural and urban areas, respectively)(Table 2).

Environmental footprints

Mean environmental footprints for households consuming an Adequate diet were 2.1 kgCO_2-eq of GHG emissions, 3.1 m^3 of WFs, and 5.8 m^2 of LU, per consumer unit/day, and increased across higher MPCE quartiles. Comparatively, households eating Relatively Healthy and Healthy diets had higher footprints for all three environmental indicators (2.2 kgCO_2-eq, 3.0 m^3, 5.9 m^2, and 2.3 kgCO_2-eq, 3.3 m^3, 6.3 m^2, per consumer unit/day, respectively).

Environmental impacts for the lower footprint versions of the health-oriented diets were 1.6 kgCO_2-eq, 2.7 m^3, 4.8 m^2 for Relatively Healthy, and 1.7 kgCO_2-eq, 2.8 m^3, 4.9 m^2 for Healthy diets, per consumer unit/day, respectively (Figure 1).

Dietary costs

The mean cost of an Adequate Indian diet at the household level, in 2011-2012, was Rs 138 per day. In comparison, the mean costs of Relatively Healthy diets and

Healthy diets were Rs 161 and Rs 171 per day, respectively. The mean costs of improved diets with lower footprints were less than the respective diets that only contained health considerations. A Relatively Healthy diet with lower footprints had a mean cost of Rs 147 per day, while a Healthy diet with lower footprints had a mean cost of Rs 152 per day (Table 3).

Use of linear regression models mostly showed statistically significant increases in costs of improved diets against the Adequate diet (except in the case of one out of the four improved diets). At the national level, when adjusting for region, rural or urban residence, MPCE, household size, and dietary energy, the differences in costs between the improved and Adequate diets were less than when comparing unadjusted mean costs, though still more expensive. A Relatively Healthy diet was Rs 7.5 higher than an Adequate diet, while a Healthy diet was Rs 18.4 higher (5% and 13% more, respectively; $P < 0.001$). Relatively Healthy diets with lower footprints were just Rs 0.3 higher than an Adequate diet (though not statistically significant), and Rs 4.1 higher for Healthy diets with lower footprints (0.2 and 3% more, respectively; $P < 0.001$)(Table 5).

These national level results masked more substantial variation among economic status quartiles and rural or urban residence. The largest difference in cost between an Adequate and Healthy and lower footprint diet was among households in the first MPCE quartile, and this difference in cost progressively decreased for those in higher MPCE quartiles. For example, for households in the first MPCE quartile, a lower footprint diet that was Relatively Healthy was Rs 12.9 more per day than for an Adequate diet, and Rs 22.8 for a lower footprint and Healthy diet (13 and 23% more, respectively, $P < 0.001$). Comparatively, for those in the highest MPCE quartile, a lower footprint diet that was Relatively Healthy was Rs 9.0 ($P < 0.001$) cheaper, and a lower footprint and Healthy diet Rs 1.5 cheaper (though not statistically significant), than an Adequate diet. Among rural households, Relatively Healthy and Healthy diets with lower footprints were Rs 4.3 (3%) and 6.9 (5%) more expensive ($P < 0.001$), respectively, while in urban areas, the Relatively Healthy diet with lower footprints was Rs 2.3 (2%, $P < 0.001$) cheaper, while a Healthy diet with lower footprint had a small, but not statistically significant, increase in price of Rs 2.6 (2%)(Table 6).

When directly comparing healthy diets with and without environmental considerations, a Relatively Healthy diet with lower footprints was Rs 14.1 cheaper than one with higher footprints ($P < 0.001$), and a Healthy diet with lower footprints was Rs 16.3 cheaper than one with higher footprints ($P < 0.05$)(Table 5).

Difference in expenditure on food groups

To assess which food groups contributed most to the increased cost of improved diets, we tested the difference in expenditure on food groups between the dietary categories. We ran the first linear regression model adjusting for region, rural or urban residence, MPCE, household size, and dietary energy. At the national level, Healthy diets with lower footprints showed a Rs 86.0 higher expenditure on fruits and vegetables combined, compared to Adequate diets ($P < 0.001$). This was followed by Rs 37.3 higher expenditure on oils and butter ($P < 0.001$), and Rs 24.6 higher expenditure on pulses ($P < 0.001$); lower expenditure was seen for meat and dairy ($P < 0.001$). The ranking of food groups for the Relatively Healthy with lower footprint diets was similar, with fruit and vegetables contributing most to the higher cost, followed by pulses, and then oils and butter. When using a second model additionally adjusting for price paid per kg of the food, the trends were the similar, in that fruit and vegetables, followed by pulses, contributed to the higher cost of improved diets, while oils and butter did not contribute to an increase in cost (Tables 7A and B).

Discussion

We found that at the national level, most improved dietary patterns were more expensive than an average Adequate diet in India. Differences in cost ranged from Rs 4 per day higher for a Healthy diet with lower footprints compared to an Adequate diet, and Rs 18 per day higher for a Healthy diet. Much of the difference in the cost of a health-oriented diet with lower footprints was due to expenditure on fruits and vegetables, as well as pulses. Of particular concern, our analyses among population sub-groups highlighted that the difference in costs between Adequate and improved diets with lower footprints was highest for lower-income households, and for those in rural areas. Conversely, the results pointed to opportunities in some cases. For urban households, as well as those in the highest wealth quartile, eating a Healthy or Relatively Healthy and lower footprint diet may be less expensive, or show no difference in cost, than the average Adequate diet. Additionally, for households already eating a Relatively Healthy or Healthy diet, the cost of a similar health-oriented diet with lower footprints would also be lower.

While still preliminary, the literature on the affordability of a healthy and environmentally sustainable diet is mixed. Studies have found that observed diets that are healthier and more sustainable can be more expensive[20-23], and less expensive[24-26] than an average diet. These studies have been conducted at the national level in HICs, and our results show that, depending on the population sub-sample used, healthy and low footprint diets can also be more or less expensive than an average diet. In our analysis, the Relatively Healthy and Healthy diets with lower footprints both had fewer calories than an Adequate diet, though when adjusted for dietary energy intake, we still found these improved diets to be slightly more expensive than the Adequate diet (though the increase for the Relatively Healthy diet with lower footprints was not statistically significant).

Only one other peer-reviewed study to our knowledge has directly compared the cost of a healthy vs. a healthy and environmentally sustainable diet; based on French dietary data, it found that a healthier and more sustainable diet was less expensive than a healthy diet[24]. Our results indicate the same.

In some instances where we found higher costs of improved diets, the absolute difference was somewhat small. For example, after adjusting for a number of variables, a Healthy and lower footprint diet nationally was only Rs 4.1, or 3%, higher than an Adequate diet; in rural areas, the increased cost was similarly Rs 4.3, or 3%. While seemingly small, it is difficult to estimate whether it would be affordable for these households to shift to the improved diets, given that we had also calculated that food expenditure as a share of total household expenditure was very high, at 70, 63, 54 and 45% across MPCE quartiles (data not shown). This is in the range of other work showing that the mean proportion of household income spent on food was about 50% in India[51], and 62% in South Asian countries[9], suggesting there may little flexibility for accommodating even small increases in dietary cost. Nonetheless, even small absolute higher costs represent an additional barrier to the crucial goal of adopting healthier (and more sustainable, where relevant) diets – and particularly so for households facing poverty, who likely face much higher expenditure gaps between current and healthy diets than those assessed here.

We found that, of the five dietary guideline components that we used to define Healthy diets, recommended intake of fruit and vegetables had the lowest rates of adherence, and was particularly low among lower-income households. We also found that fruit and vegetables are among the most expensive components of adopting a healthier and lower footprint diet. This agrees with work in both HIC and LMICs showing that lower-income individuals tend to consume fewer fruits and vegetables[9], and that fruit and vegetables are among the main drivers of the higher cost of improved diets[9,52-54]. Additionally, prices of fruit and vegetables globally in the last decade have been rising faster than other food groups[12,52] - particularly processed foods - and a continuation of these trends raises further risks for the future affordability of healthier diets. Higher expenditure on pulses was also associated with healthy and lower footprint diets in our results; while we did not use any specific guidelines on pulses, their higher intake in improved diets may be due to their relative affordability and lower environmental footprints compared to meat[16,37], and high protein content relative to dietary energy content[38].

Differences in the mean unadjusted cost between Adequate and improved diets were high (6 and 10% higher for Relatively Healthy + LF, and Healthy + LF diets, respectively), though after adjusting for various demographic variables and dietary energy intake, the differences decreased to about <1 and 3%, respectively. Therefore it is likely that factors other than the mix of food groups themselves contribute to the higher cost of improved diets. Relative price paid per food group increases moderately across wealth quartiles (data now shown), and may be due to discretionary spending at higher-cost markets among wealthier households (i.e., supermarkets vs. street vendors), purchasing of higher-quality items, or may reflect the lack of reliable access to food, and therefore higher prices, as seen in the rural sub-sample in this analysis.

We defined lower footprint diets as having reduced GHG emissions, WFs, and LU. This is the first study to our knowledge to assess the costs of diets with lower impacts across a number of footprints, as other similar studies only use GHG emissions. It is important to assess multiple indicators in sustainable diets analyses, as some dietary patterns may be beneficial for one environmental indicator, while being less so, or even detrimental, for another indicator[7]. In our sample, there were very small differences between the mean costs of diets lower in single environmental footprints (i.e., lower in LU, or WFs, or GHG emissions), though all of these were slightly more expensive than a comprehensively lower-footprint diet (data not shown). However, the fully comprehensive lower footprint diet had about one-third fewer adherents in the sample, indicating that it may be less realistic.

Healthy diets are based on high intake of fruit and vegetables, and the required higher expenditure on these food groups may be further compounded by several factors: these food groups are particularly susceptible to high price volatility in

India[55], and globally, South Asia tends to experience the most frequent food production shocks, which may exacerbate price barriers[56]. Fruit and vegetables additionally exhibit high price elasticity, meaning that, relative to other food groups, demand drops most when prices increases[57]. In this context, strategies to improve the affordability and accessibility of fruit and vegetables, among other nutrient-rich foods, are important to pursue [5,58,59]. This will likely require a variety of approaches across food systems, including reducing waste, increasing agricultural yields, improving distribution, appropriate pricing mechanisms to better enable healthy choices, as well as improving knowledge around healthy diets[10,60-63].

Our results should be interpreted in the context of several limitations. The food purchase data we used may not represent actual intakes, as some purchased food may be uneaten or wasted. The survey may suffer recall bias, though this exists to some degree in all dietary surveys. We have based our categorisation of healthy diets partly on absolute fruit and vegetable intake, while substantial variation in intake of these food groups was found in a recent comparison of dietary data sources in India; discrepancies were also particularly high for other nutrient-dense food groups such as animal-based products[39]. However, we used the “type 2” format of the survey, which included 7-day, rather than 30-day recall for nutrient-dense food groups, which may have reduced recall bias to some degree, and comparison of the NSS data to another national household expenditure survey yielded similar intakes of broad food groups[39]. We also assumed that meals eaten out of home, for which further details on food group composition are not available, represented the same proportion of food groups as purchased by the household.

The 68th NSS round, conducted in 2011-12, was the most recently available nationally-representative data available for this analysis, though given India's high food inflation[64], absolute dietary expenditures have likely risen significantly. However, our trends on the higher cost of healthy and lower footprint diets are unlikely to have changed, as the costs of fruits and vegetables continue to rise compared to other food groups in India[52]. We used average national values of environmental footprints; while the analysis could be improved with the use of footprint data at lower scales, where available, incorporating these would require more detailed knowledge than is currently available on the regional source of food groups consumed within a given location. There is a lack of criteria by which to judge a sustainable diet in absolute terms, and we therefore used "below average" footprints. However, simply reducing relative footprints may not be a sufficient criterion to enable food systems to deliver nutritious diets over the long-term within environmental planetary boundaries[65]. However, a strength of our study is the use of multiple environmental indicators, and recent work is beginning to derive environmental targets for food systems at the global level[66]. Micronutrient deficiencies remain a substantial challenge in India; we did not include micronutrient RDAs in our Healthy category, as these would be difficult to reliably assess in the context of the household-level expenditure data. Instead, we used the high-level recommendations from the NIN[47] on macronutrients (energy, protein, and fats), and adequate fruit and vegetable intake, which match those of WHO/FAO[67]. We have assumed that these guidelines would provide a realistic and easy to understand healthy scenario, though we may have assigned some micronutrient-deficient households to the Healthy category.

Conclusion

Healthy and lower footprint diets in India are currently more expensive than average calorically-adequate diets for those in rural areas and among lower-income households. However, we also found opportunities of lower or no difference in costs of these improved diets in urban regions, and generally those in wealthier households. Fruits and vegetables, as well as pulses, were found to contribute most to the higher cost of improved diets. While the higher costs of improved diets in some cases were small in absolute terms, they nonetheless represent an additional barrier to uptake of healthy diets, and particularly so for households experiencing undernutrition, whom our analysis did not include. Efforts must be made to increase the affordability and accessibility of fruits and vegetables, among other nutrient-rich food groups, to improve both health and environmental sustainability in India.

Table 1: Details of dietary categories used in analysis.

Dietary category	Description	Dietary guideline targets: Dietary energy (kcal/day)	Percent dietary energy from protein (%)	Percent dietary energy from fat (%)	Fruit intake (g/day)	Vegetable intake (g/day)
Adequate	At least meeting the minimum recommended dietary energy for low-activity individuals.	As per age- and sex-specific composition of household	N/A	N/A	N/A	N/A
Relatively Healthy (and lower footprints)	Relaxation of guidelines on fruit and vegetables (to 60% of total recommended fruit and vegetable intake, reflecting 3 out of 5 servings for adults, and recommendations scaled respectively for children and elderly), and percent of calories from fat; dietary energy and percent of calories from protein adhere to dietary guidelines. **Lower footprint** households in this category additionally had GHG emissions, WFs and LU lower than mean footprints.	As per age- and sex-specific composition of household	10-15	19.5-30	60% of combined recommended household intake of fruit and vegetables	
Healthy (and lower footprints)	Adherence to dietary guidelines for dietary energy intake, percent of calories from protein and fat, and fruit and vegetable intake. **Lower footprint** households in this category additionally had GHG emissions, WFs and LU lower than mean footprints.	As per age- and sex-specific composition of household	10-15	20-30	As per age- and sex-specific composition of household	As per age- and sex-specific composition of household

Notes: see Supplementary table 2 for age- and sex-specific dietary guidelines for dietary energy, fruit and vegetable intake.

Table 2: Number of households by dietary category.

	All India	Adequate		Relatively Healthy		Healthy		Relatively Healthy + lower footprints		Healthy + lower footprints	
	no.	**no.**	**% of total**	**no.**	**% of adeq.**	**no.**	**% of adeq.**	**no.**	**% of adeq.**	**no.**	**% of adeq.**
Rural	59,277	37,548	63%	5,452	12%	637	1%	2,560	6%	225	1%
Urban	41,061	21,677	53%	5,473	19%	1,083	4%	2,464	9%	336	1%
Total	100,338	59,225	59%	10,925	15%	1,720	2%	5,024	7%	561	1%
MPCE											
Q1	25,294	11,121	44%	666	6%	18	<1%	458	4%	14	<1%
Q2	25,267	14,857	59%	2,323	13%	177	1%	1,383	8%	91	1%
Q3	25,156	15,942	63%	3,872	19%	516	3%	1,815	9%	202	1%
Q4	24,621	17,305	70%	4,064	18%	1,009	5%	1,368	6%	254	1%

Notes: MPCE, mean per capita expenditure.

Table 3: Descriptive characteristics by dietary category.

	Total	Adequate	Relatively Healthy	Healthy	Relatively Healthy + LF	Healthy + LF
	Mean (95% CIs)					
Household size	4.6 (4.6 to 4.6)	4.4 (4.4 to 4.4)	4.3 (4.3 to 4.3)	3.5 (3.5 to 3.6)	4.4 (4.3 to 4.4)	3.6 (3.5 to 3.8)
MPCE	2217 (2204 to 2230)	2385 (2367 to 2404)	2865 (2829 to 2902)	3844 (3725 to 3963)	2617 (2567 to 2667)	3364 (3188 to 3539)
Dietary cost (Rs/d)	132.5 (132.0 to 133.0)	138.3 (137.7 to 139.0)	160.8 (159.3 to 162.3)	170.8 (166.6 to 174.9)	147.2 (145.3 to 149.1)	151.5 (145.6 to 157.5)
GHGE (kgCO_2-eq/d)	6.7 (6.6 to 6.7)	7.1 (7.1 to 7.2)	7.7 (7.6 to 7.8)	6.8 (6.6 to 7.1)	5.6 (5.5 to 5.7)	5.1 (4.9 to 5.3)
WF (m^3/d)	9.9 (9.9 to 9.9)	10.5 (10.4 to 10.5)	10.5 (10.5 to 10.6)	9.6 (9.4 to 9.8)	9.7 (9.6 to 9.8)	8.5 (8.2 to 8.8)
LU (m^2/d)	18.7 (18.7 to 18.8)	19.7 (19.6 to 19.8)	20.4 (20.2 to 20.6)	18.2 (17.7 to 18.7)	17.3 (17.1 to 17.5)	14.8 (14.2 to 15.3)

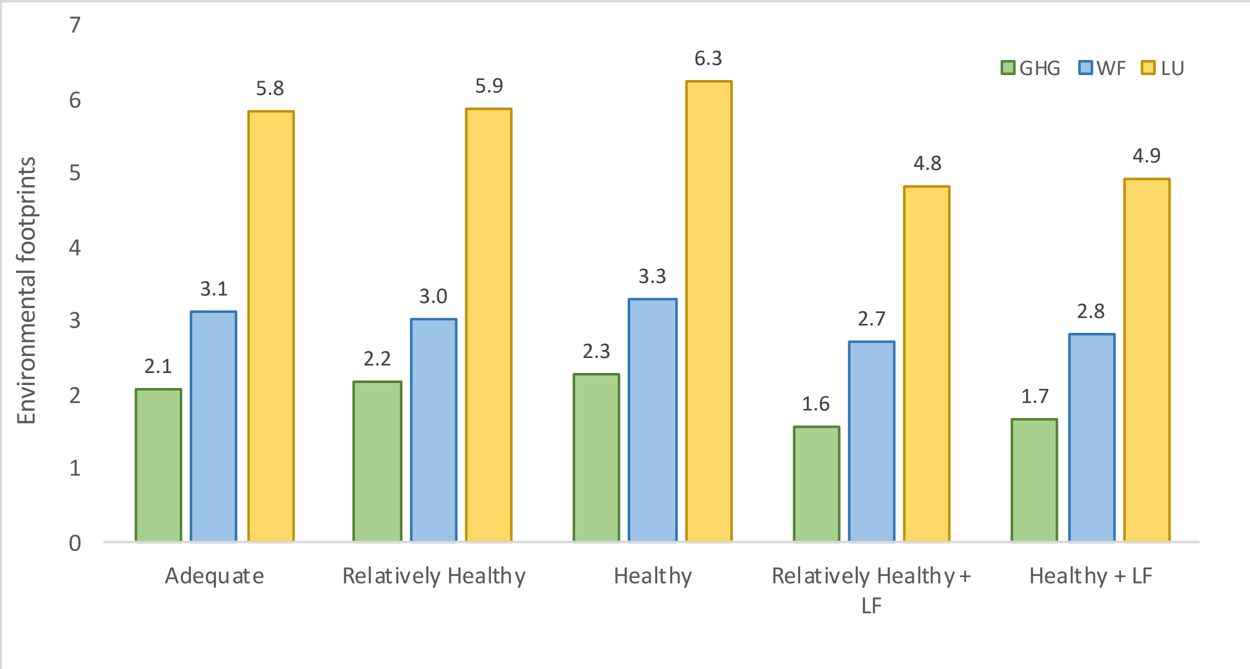
Notes: MPCE, mean per capita expenditure. LF, lower than average footprint; GHGE, greenhouse gas emissions; WF, water footprint; LU, land use.

Table 4: Proportion of households meeting components of healthy dietary guidelines.

	Dietary energy	Proportion dietary energy from protein	Proportion dietary energy from fat	Fruit intake	Vegetable intake
Rural	59%	69%	34%	26%	21%
Urban	55%	71%	47%	38%	23%
Total	57%	70%	39%	31%	22%
MPCE					
Q1	44%	58%	26%	10%	9%
Q2	61%	69%	37%	21%	17%
Q3	66%	75%	45%	36%	25%
Q4	58%	77%	50%	57%	38%

Notes: MPCE, montly per capita expenditure.

Figure 1: Environmental footprints of households, per consumer unit, by dietary category, at the national level.



Notes: LF, lower than average footprint; GHG, greenhouse gas emissions; WF, water footprint; LU, land use. Units for footprints are as follows: GHG, $kgCO_2$-eq; WFs, m^3; LU, m^2. One consumer unit is the dietary energy requirement of an adult male (ages 18-59), assuming moderate physical activity, equivalent to 2730kcal/day.

Table 5: Difference in cost between dietary categories, at the national level.

	Unadjusted	Adjusted
Adequate vs. healthy diets		
Adequate (reference)	-	-
Relatively Healthy	**22.5 (20.8 to 24.2)**	**7.5 (6.6 to 8.4)**
Healthy	**32.4 (28.5 to 36.4)**	**18.4 (16.4 to 20.4)**
Adequate vs. healthy and sustainable diets		
Adequate (reference)	-	-
Relatively Healthy + LF	**8.9 (6.5 to 11.2)**	0.3 (-0.9 to 1.5)
Healthy + LF	**13.2 (6.4 to 20)**	**4.1 (0.7 to 7.5)**
Healthy vs. healthy and sustainable diets		
Relatively Healthy + HF (reference)	-	-
Relatively Healthy + LF	**-26.1 (-28.8 to -23.3)**	**-14.1 (-15.4 to -12.7)**
Healthy + HF (reference)	-	-
Healthy + LF	**-28.5 (-37.3 to -19.7)**	**-16.3 (-20.5 to -12.0)**

Notes: coefficient values in bold are statistically significant at the 5% level. LF, lower than average footprint; HF, higher than average footprint. Regression models are adjusted for region, rural/urban, mean per capita expenditure, household size, and dietary energy intake.

Table 6: Difference in cost between dietary categories, by MPCE quartiles and rural/urban residence.

	MPCE Q1		Q2		Q3		Q4		Rural		Urban	
	Unadj.	**Model 1**	**Unadj.**	**Model 1**	**Unadj.**	**Model 1**	**Unadj.**	**Model 1**	**Unadj.**	**Model 1**	**Unadj.**	**Model 1**
Adequate (reference)	-	-	-	-	-	-	-	-				
Relatively Healthy + LF	**21.9 (17.3 to 26.5)**	**12.9 (10.8 to 15.1)**	**15.5 (12 to 18.9)**	**7.3 (5.9 to 8.8)**	**8.3 (4.7 to 11.9)**	**2.7 (1.1 to 4.3)**	**-12.4 (-18 to -6.7)**	**-9 (-12.3 to -5.8)**	**10.3 (7.3 to 13.4)**	**4.3 (2.8 to 5.8)**	2.4 (-1.2 to 6.1)	**-2.3 (-4.2 to -0.4)**
Healthy + LF	9.9 (-16 to 35.7)	**22.8 (11.1 to 34.5)**	9.2 (-3.8 to 22.2)	**12.9 (7.6 to 18.2)**	**15.2 (4.9 to 25.5)**	**9.7 (5.3 to 14.2)**	**-17.4 (-30.2 to -4.6)**	-1.5 (-8.6 to 5.5)	8.9 (-1.3 to 19)	**6.9 (2.1 to 11.7)**	8.7 (-0.9 to 18.2)	2.6 (-2.2 to 7.4)

Notes: coefficient values in bold are statistically significant at the 5% level. LF, lower footprint; coeff., regression coefficient; unadj., unadjusted; adj., adjusted. Model 1 is adjusted for region, rural/urban, mean per capita expenditure, household size, and dietary energy intake.

Table 7A: Difference in household expenditure between dietary categories on cereals, oils and butter, pulses, fruit and vegetables, at the national level.

	Cereals		Oils/butter		Pulses		Fruit		Vegetables	
	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2
Adequate (reference)	-	-	-	-	-	-	-	-	-	-
Relatively Healthy + LF	**-18.9 (-28.5 to --9.3)**	**-16.6 (-23.5 to -9.8)**	**11.9 (7.4 to 16.4)**	**-5.1 (-8.3 to -1.8)**	**16.1 (12.5 to 19.7)**	**10.7 (7.2 to 14.1)**	**13 (10.9 to 15.1)**	**11.4 (9.1 to 13.6)**	**15.8 (14.2 to 17.5)**	**15.7 (14.2 to 17.3)**
Healthy + LF	**-25.7 (-52.7 to -1.4)**	**-39.5 (-58.7 to -20.4)**	**37.3 (24.5 to 50.0)**	-5.8 (-15.0 to 3.4)	**24.6 (14.5 to 34.7)**	**18.5 (8.7 to 28.2)**	**37.6 (31.7 to 43.5)**	**31.7 (25.6 to 37.9)**	**48.4 (43.8 to 53.0)**	**50.3 (45.8 to 54.7)**

Notes: coefficient values in bold are statistically significant at the 5% level. LF, lower footprint. Model 1 adjusted for region, rural/urban, mean per capita expenditure, household size, and dietary energy intake; model 2 adjusted for price paid per kg of respective food group, in addition to variables controlled for in model 1.

Table 7B: Difference in household expenditure between dietary categories on dairy, meat and eggs, at the national level.

	Dairy		Meat		Eggs	
	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2
Adequate (reference)	-	-	-	-	-	-
Relatively Healthy + LF	14.7 (-3.6 to 33)	-7.6 (-26.7 to 11.4)	**-17.1 (-21.6 to -12.7)**	-3.3 (-11.1 to 4.5)	**-0.8 (-1.4 to -0.2)**	0.3 (-0.9 to 1.4)
Healthy + LF	**-57.9 (-109.4 to -6.5)**	**-74.5 (-128 to -21.0)**	**-41.8 (-54.2 to -29.4)**	-16.8 (-42.9 to 9.3)	**-2.8 (-4.5 to -1.2)**	2.5 (-1.3 to 6.2)

Notes: coefficient values in bold are statistically significant at the 5% level. LF, lower footprint. Model 1 is adjusted for region, rural/urban, mean per capita expenditure, household size, and dietary energy intake; model 2 is adjusted for price paid per kg of respective food group, in addition to variables adjusted for in model 1.

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Supplementary table 1: Environmental footprints of food groups.

Food group	GHG emissions ($kgCO_2$-eq/kg food)	Green WF (m^3/kg food)	Blue WF (m^3/kg food)	Land use (m^2/kg food)
Cereals - wheat	0.540	0.985	1.366	2.867
Cereals - rice	1.614	2.072	0.715	4.227
Cereals - other	0.725	4.171	0.066	8.468
Dairy - lo-fat	2.524	0.845	0.285	2.016
Dairy - hi-fat	6.851	2.718	0.917	4.732
Dairy - butter/ghee	12.531	4.321	1.458	10.268
Fish, seafood	1.172	0.670	0.295	-
Fruit - mango	0.115	1.237	0.566	1.517
Fruit - orange	0.264	0.678	0.003	1.010
Fruit - guava	0.117	1.237	0.566	1.606
Fruit - banana	0.195	0.266	0.193	0.338
Fruit - papaya	0.117	0.267	0.087	0.278
Fruit - grapes	0.586	0.289	0.336	0.510
Fruit - melon	0.610	0.265	0.025	0.559
Fruit - other	0.117	1.158	0.218	1.038
Meat - poultry	1.425	11.782	2.530	30.631
Egg	1.119	7.721	1.658	16.987
Meat - mutton	63.531	4.872	0.290	52.913
Meat - other	1.425	3.324	0.272	5.162
Legumes	1.759	1.606	0.129	4.869
Nuts and seeds	1.286	9.410	1.525	13.358
Other - sugar	0.504	0.925	0.995	1.294
Pulses - red gram	1.398	5.068	0.282	18.213
Pulses - other	1.261	3.114	0.323	10.814
Veg - onion and garlic	0.740	0.164	0.143	0.653
Leafy veg	0.155	0.412	0.046	0.466
Spices - other	1.254	3.626	0.424	4.521
Potato	0.497	0.218	0.038	0.565
Veg - tomato	0.138	0.223	0.043	0.523
Veg - gourd	0.212	0.375	0.012	1.301
Veg - carrot	0.703	0.082	0.060	0.724
Veg - other	0.201	1.059	0.217	0.466
Veg oils	0.746	9.541	0.867	35.868

Supplementary table 2: Selected healthy dietary guidelines by age and sex.

	Age (years)	Energy (kcal/d) Moderate	Low	High	Veg intake (g/d)	Fruit intake (g/d)
Males	<1	584	496	747	55	55
	1-3	1060	901	1355	100	100
	4-6	1350	1147	1726	150	100
	7-9	1690	1436	2160	200	100
	10-12	2190	1861	2800	300	100
	13-15	2750	2337	3516	300	100
	16-17	3020	2566	3861	300	100
	18-59	2730	2320	3490	300	100
	60-69	2184	1856	2792	240	80
	70+	1911	1624	2443	210	70
Females	<1	584	496	747	55	55
	1-3	1060	901	1355	100	100
	4-6	1350	1147	1726	150	100
	7-9	1690	1436	2160	200	100
	10-12	2010	1708	2570	300	100
	13-15	2330	1980	2979	300	100
	16-17	2440	2074	3119	300	100
	18-59	2230	1895	2851	300	100
	60-69	1625	1381	2077	240	80
	70+	1593	1354	2036	210	70

Note: Moderate, low and high refer to physical activity level. The vegetable intake recommendation for adults allowed at most 50 g/d of potatoes within the total 300 g/d; this requirement was scaled accordingly for other ages.

Supplementary table 3: Worked example of estimating household adherence to dietary energy guidelines.

Household member	Sex	Age	Dietary energy recommendation	Observed intake
1	F	3	901 to 1355	-
2	F	29	1895 to 2851	-
3	M	30	2320 to 3490	-
Total	-	-	5116 to 7696	6000

Note: in this worked example, the household would fall within dietary energy guidelines.

Supplementary File 1

Adjustments made to reported food purchase in National Sample Survey household consumer expenditure data.

Dietary data were adjusted for high-income households that provide food to poorer households in exchange for labour or services as follows:

$$adjusted\ intake = \ C_i\left(\frac{M_h + M_f}{M_h + M_g}\right)$$

where *C* is the unadjusted intake of food item *i*, M_h is the number of meals consumed by the household members, M_f is the number of meals received free from other households by household members, and M_g is the number of meals consumer by non-members (guests, employees, etc.).

Data were additionally adjusted for foods eaten out of home. NSS records purchase of ~140 individual foods which we matched to nutritional composition data for our analysis. However, some of the recorded purchases are of a variety meals and snacks outside of home, which we were not able to break down into food groups required for our analysis, such as fruits and vegetables. To approximate intake of food groups from these meals and snacks, we used the NSS data on estimated caloric content of out of home meals. We took the proportion of these out of home calories out of all calories, and then scaled the individual food items purchased by this proportion. This adjustment assumed that the distribution of food groups in the meals purchased out of home was the same as the household's purchased food items.

7. Overall discussion and conclusions

A growing body of literature has pointed to the potential health and environmental benefits of shifting current average diets in HICs to a number of more sustainable dietary patterns, while the literature on the affordability of such diets has been mixed. In this PhD project, I have investigated these relationships first with a systematic review of the global literature, mainly based on studies in HICs, and then with a focus on India, chosen because of its large population, data availability, rapidly evolving changes in diet, and vulnerability to environmental change. For India, I have compared available Indian dietary data for suitability for sustainable diet analyses; estimated the changes in GHG emissions, LU and WFs that would result from a national adoption of dietary guidelines; and lastly, calculated the costs of observed healthy, and healthy and lower-footprint diets in India, to assess their affordability. This discussion section first summarises the findings of each paper, then ties together the results and outlines the implications of the findings, describes the limitations of the overall project, and proposes future areas of work based on the gaps in knowledge identified during this research.

7.1 Main findings

While the literature generally shows an environmental benefit of shifting from typical Western diets to more sustainable diets, studies use heterogeneous approaches across numerous types of sustainable diets proposed, for different countries, and assess different environmental footprints. **Paper 1** was a systematic review of the area, with the aim of teasing out relative trends across the literature. The major findings were a simple typology of sustainable diets proposed (about 14, with several more sub-iterations), and a ranking of the sustainable diet types by their resulting median change in environmental impact (compared to a typical Western diet), across three environmental indicators (GHG emissions, water and land use). The review also found positive health effects of adopting sustainable diets, though there were fewer results on health than on environmental impacts. The range of environmental impacts due to dietary change was wide both across sustainable diet categories, and within each category. For example, median impacts across diet categories ranged from a 45% reduction in GHG emissions for a vegan diet, to a reduction of only 2% from a diet replacing meat with dairy products; while within vegan diets, impacts at the 1st and 3rd quartiles ranged from a 70% reduction to about a 20% reduction. Nonetheless, the ranking of the diet types with the highest environmental benefits showed similarities across GHG emissions, LU and WFs; these were diets that most reduced the amount of animal source foods, including vegan, vegetarian and pescatarian diets. Conversely, diets with the least reductions in animal source foods, such as restricting dietary intake overall, and substituting dairy for meat, showed the least benefit. Interestingly, there were cases of environmental trade-offs: in some scenarios, sustainable diets increased footprints. This could be explained by variation across environmental indicators in the relative environmental benefit of plant-based foods versus animal source foods; for example, while pulses generally have fewer GHG emissions than animal source foods, they may have similar or sometimes higher WFs than some animal source foods, and therefore a shift from some meats to pulses could increase water use while reducing emissions. Adoption of sustainable diets generally showed a lower magnitude of WF benefits compared to GHG emissions and LU, which could be due to a similar trend.

Another systematic review of sustainable diets, published around the same time as **Paper 1**, found that in some cases, low-GHG emission diets on their own, without having specific health considerations, may be detrimental to health[231]. This is likely, as some nutrient-poor foods, such as sugar and potatoes, have some of the lowest environmental impacts[26,27,116].

As a first step to investigating the environmental impacts and affordability of dietary change in India, **Paper 2** assessed the NSS household expenditure survey against a set of other dietary data sources in India, to better inform the data selection and use for the project. An early decision point in the project was which of the available dietary data sources in India could be used for the analysis, including, among others, the Indian Migration Study or the NSS data, both with respective strengths and limitations.

Despite the long use of the NSS data in government statistics and the published literature, there was almost no literature examining the relative validity of the dietary purchase data. This analysis compared overall intake of food in grams/person per day, as well as intake of major food groups, across 12 data sources, using NSS as a reference comparison (with food purchase and availability data being used as a proxy for dietary intake). A major task in this work was cleaning and formatting the raw data for eight of these datasets, while the remaining four (two rounds each of FBS and National Nutrition Monitoring Bureau (NNMB)) were drawn directly from online databases and reports.

The comparison found that the two different national expenditure surveys (NSS and the IHDS), averaged across two different survey rounds, were most similar to each other. The FBS data were most dissimilar to the NSS, followed by the IMS FFQ, and the NNMB 24-hr recall surveys. Intake of key food groups, important for both health and environmental considerations, such as eggs, meat, fruit and nuts, varied widely across the datasets, while intake of cereals showed remarkable consistency. Additionally, the puzzling trend in decreasing caloric intake recorded in the last several decades of the NSS data, and discussed widely in the literature[232], was not reflected in other national-level data sources (FAO and IHDS). Other literature has also highlighted that FBS tend to overestimate intake[153,206,233], but comparisons between other types of dietary surveys are variable depending on the specific format, respondent type, and length of the surveys[234-236].

Paper 3 calculated the change in environmental footprints (GHG emissions, LU and WFs) that would result from adoption of healthy diets nationally, as well as from an alternative scenario of adoption of “affluent diets” (representing intake of households in highest quartile of wealth). This work pulled together four separate data sources, on dietary intake and three environmental indicators, and an early abstract of this work was the first to estimate environmental impacts from dietary change in India[237].

This study found that at a national level, environmental footprints would increase slightly, by 3-5% across GHG emissions, blue and green WFs, and LU, as a result of adoption of healthy diets. A healthy diet, compared to the mean current diet, was characterised largely by increased vegetable intake, and a small increase in fruit and dietary energy. The change in environmental impacts differed by sub-samples of the population: for those estimated to consume above recommended dietary energy, footprints would decrease by 6-16%, while for those estimated to consume less than recommended dietary energy, footprints would increase by 18-41%. The average increase in footprints was slightly lower in rural areas at 1-5%, compared to 5-9% for urban areas. Alternatively, adoption of affluent diets nationally would result in increases of 19-36% across footprints. Affluent diets were characterised by high dietary energy, high intake of fruit and vegetables (though the latter not meeting recommended guidelines), and higher meat and dairy intake, and proportion of energy from fats, compared to average Indian diets.

Indian agriculture faces substantial environmental pressures in the form of limited additional availability of agricultural land, and water for irrigation. The results suggest that, contrary to work in HICs, a shift to healthier diets may not in itself be a strategy to lower environmental footprints - though important environmental benefits from healthy diets could potentially be realised among populations who currently consume above recommended dietary energy. The results highlight that it will be important to pursue agricultural measures such as decreasing waste and improving yields, alongside dietary change, to enable the provision of healthy diets while limiting environmental impacts in India.

Given the potential opportunity to realise health and environmental benefits through dietary change among those eating at least adequate dietary energy in India, **Paper 4** assessed the affordability of diets that are healthier, as well as those that are both healthier and more environmentally sustainable, compared to an average diet with adequate dietary energy in India. While the work is yet to be submitted for publication, the analysis is, to my knowledge, the first to assess the costs of observed healthy and low-footprint diets in India.

Two categories of healthiness were measured; Healthy, which followed dietary guidelines, and Relatively Healthy, which was largely characterised by three servings of fruit and vegetables, as opposed to five in the Healthy category. Additionally, individuals were flagged as having a lower environmental footprint if their diet-related GHG emissions, WFs, and LU were lower than average sample footprints. The costs of these diets were compared to an average Adequate diet that met minimum dietary energy requirements. This study found that, firstly, very few individuals are estimated to be consuming healthy diets nationally, at about 2% in the sample. The less stringent Relatively Healthy diet was estimated to be consumed by a higher proportion, at 15%. Lower footprint versions of these diets had very low prevalence, at less than 1 and 7%, respectively. The cost of a lower footprint diet that was Healthy was 3% higher than an Adequate diet, while the difference in cost for the Relatively Healthy version was not statistically significant. Some opportunities were found among population sub-samples, including improved diets having no difference in cost or being cheaper for individuals in the highest income quartile, and for individuals in urban areas. Conversely, for those in rural areas, or among those in lower income quartiles, improved diets were more expensive than average diets. Food as a proportion of household expenditure in these latter samples was high, at 60-70%, so even small cost increases for an improved diet would likely be difficult to accommodate. This study extends the limited set of results on costs of observed healthy and low-footprint diets in HICs, which to date have been mixed, with findings that such diets are both more[81,82] and less[83,86] expensive than an average diet.

7.2 Implications

This section explores the opportunities to improve both health and diet-related environmental footprints in India, first by briefly comparing the results on environmental impacts of dietary changes across the systematic review (**Paper 1**) and the two results papers in this PhD (**Papers 3 and 4**), and then by discussing relevant recommended strategies.

Synthesis of results

Table 2 below summarises and compares the environmental footprints of adopting national dietary guidelines across the papers in the PhD. The scenarios reviewed in **Paper 1**, and assessed in **Papers 3** and **4**, feature different parameters (hypothetical modelled diets vs. observed actual diets, using total population vs. using adults, etc.), and while not directly comparable, still serve as a useful contrast to examine the features of healthy and environmentally sustainable diets in India.

The systematic review (**Paper 1**) found that a shift from average Western diets to healthy dietary guidelines in HICs resulted in median impacts across studies of -12% in GHG emissions, -6% in WFs, and -20% in LU (scenario A). **Paper 3** found that in India, shifting the overall population to dietary guidelines would increase emissions (scenario B), though in a scenario among those who already consume adequate dietary energy, a shift to healthy diets could reduce footprints by 6% for GHG emissions, 13% for WFs, and 16% for LU (scenario C) – a comparable result to that of the systematic review. **Paper 4** assessed the costs and environmental footprints of observed diets among adults that adhere to dietary guidelines; it found that healthy diets, which had higher dietary energy content and more dairy than average adequate diets, also had footprints that were 16-21% higher (scenario D). However, diets that were both healthy and specifically lower footprint, had, as expected, reduced footprints compared to the average adequate diet (scenario E). The scenarios in **Paper 3** and **Paper 4** with decreased environmental footprints (scenarios C and E) shared some similarities. In **Paper 4**, compared to current adequate diets, existing healthy and lower footprint diets had overall slightly less dietary energy intake, a reduction in cereals, meat and eggs, and a higher amount of dairy, pulses, and fruit and vegetables (scenario E). In **Paper 3**, a healthy diet optimised for those who consumed above adequate dietary energy levels was largely characterised by reduced energy intake, as well as reductions in cereals, an increase in vegetable intake, and a reduction in oils, though with little change in meat and dairy intake (scenario C).

Table 2: Comparison of environmental impacts from shifting to healthy diets

Label	**Scenario description**	**Change in kcal/day**	**Change in footprints**		
			GHG	**WF**	**LU**
Paper 1					
A	Shifting average Western diet to healthy guidelines	(most scenarios were isocaloric shifts)	-12%	-6%	-20%
Paper 3					
B	Shifting all individuals to healthy guidelines	+70 (mean sample kcal: 2141 and 2211, respectively)	+4%	+5%	+4%
C	Shifting all individuals above dietary energy requirements to healthy guidelines	-403 (mean sample kcal: 2534 and 2131, respectively)	-6%	-13%	-16%

Paper 4					
D	Comparing adults above dietary energy requirements to those adhering to healthy guidelines	+141 (mean sample kcal: 2676 and 2817, respectively)	+21%	+16%	+18%
E	Comparing adults above dietary energy requirements to those adhering to healthy guidelines and having lower-footprint diets	-59 (mean sample kcal: 2676 and 2617, respectively)	-11%	-3%	-8%

These results in combination highlight several key points:

1) Given the complex nutritional challenges in India, adoption of healthy diets by all is a critical priority;

2) While mean per capita environmental footprints nationally may increase from such a strategy, there is a potential opportunity to shift those who consume above recommended dietary energy to healthier and lower-footprint diets;

3) Healthy and lower-footprint diets in India are likely to have the following features: dietary energy within recommended guidelines (and where a reduction is required, likely through a decrease in refined cereals), a high intake of fruit and vegetables, and reliance on protein from plant sources rather than animal source foods, where possible;

4) However, healthy and lower-footprint diets are not currently affordable to many citizens in India – and therefore affordability, particularly of fruit and vegetables, needs to be improved;

5) For those who can afford healthy and lower footprints diets, consumer attitudes and preferences may need to shift so as to make these dietary patterns appealing;

6) Given the overall increase in footprints at a national level from adoption of healthy diets by all individuals, strategies to improve agricultural efficiency also need to be pursued in parallel.

The sections below further discuss the latter points on improving agricultural practices, as well as the acceptability of healthy and lower footprint diets (while affordability is discussed in more detail separately in **Paper 4**).

Supply-side agricultural strategies to reduce environmental footprints

Given the increase in environmental impacts nationally from a shift to healthy diets, improvements in agricultural production are required. A full investigation of the opportunities for agricultural strategies is outside the scope of this discussion, however, the literature to date points to some low-hanging fruit. An analysis by the FAO has highlighted that a major opportunity globally to reduce environmental impacts is to improve the low-productivity ruminant livestock systems in many LMICs, and particularly in India[14]. Currently, the productivity of Indian livestock systems per quantity of GHG emissions released is half that seen in North America and Western Europe, and could be improved through better feeding, animal health, and herd management, among other practices[14,238].

Crop yields in India are also below those of HICs[116,239]. India in particular has been identified as one of six “leverage point” countries where improvements in agricultural practices could have major impacts on global agriculture-related environmental footprints, particularly for freshwater use, nitrogen and phosphorus, and methane and nitrous oxide emissions[240]. Another analysis found that by 2030, close to 20% of India's agricultural emissions could be mitigated through adoption of feasible agricultural strategies, such as zero-tillage practices, restriction of crop residue burning, and better timing of fertiliser application[241].

Food waste in India has been calculated to result in substantial environmental footprints for GHG emissions, WFs and LU (annually, 64 million tonnes of CO_2eq, 115 billion m^3, and 10 million hectares, respectively)[242]. These figures for waste alone are larger than the increased footprints calculated in the **Paper 3** analysis resulting from the adoption of healthy diets nationally (24 million tonnes of CO_2eq, 45 billion m^3, and 8 million hectares, respectively), highlighting the opportunity for waste reduction measures to more than compensate for the increased environmental footprints resulting from improving diets.

Strategies for increasing agricultural output while reducing environmental impacts may also have an additional co-benefit to farmers, as many of the improved agricultural practices are also cost-effective[241], and are likely to build resilience to the future impacts of climate change on agricultural production[243,244]. A recent estimate has shown that sufficient dietary energy is produced globally, but with insufficient fruit and vegetable production to supply the levels recommended by nutritional guidelines[245]. Agricultural improvement and higher production, particularly for fruit and vegetables, may also have the added benefit of facilitating better access to these food groups, and potentially lowering their price.

Demand-side strategies to facilitate consumer choice of healthy and low-footprint diets

Parallel to supply-side efforts to reduce the environmental impacts of agricultural production, demand-side measures will also be important to help consumers alter dietary choices. There are several barriers to dietary change: accessibility, as reliable provision of a variety of nutrient-dense foods is inadequate in many regions; affordability, as the cost of healthy diets is too high for many individuals; and consumer preferences. Challenges of access and affordability, and measures to improve them, have long been called for in India, including appropriate pricing mechanisms[67,246-248], and are a general nutrition and development goal, and not exclusive to environmental sustainability concerns. The barrier of affordability is discussed in more detail in **Paper 4**, and given that the opportunities for affordable, low-footprint and healthy diets were mostly seen among urban and higher-income individuals, who are less likely to experience inadequate access to food, this section focuses briefly on the feasibility of changing consumer dietary preferences. As mentioned above, the relevant principles of a healthy and lower footprint diet for India may be reductions in overall dietary energy (while still within healthy guidelines), through a decrease in refined cereals, an increase in fruit and vegetables, and a reliance on proteins from plant rather than animal sources. A recent study found that within cereals, a switch from refined rice and wheat to more traditional grains such as millet and sorghum could also improve nutrient intake and lower environmental footprints[74,249].

While per capita environmental footprints from diets in HICs are high, the prominence of health and environmental concerns in dietary choices seems to be rising[250], though is typically associated with middle- and high-income individuals[251]. Uptake and consumer interest in novel and healthy “superfoods” such as quinoa (though historically a traditional food in other regions), and low-footprint protein-alternatives[252,253] has been remarkably high. In India, likewise, there is a high level of public awareness and interest in choices that reflect health and environmental considerations. A study across Asia on people’s perceptions of climate change found that individuals in India are acutely aware of the issue – more so than other surveyed countries – and particularly concerned about the impacts of climate on water[254]. A global opinion poll also found that 9 out 10 Indians surveyed were concerned with local challenges of air and water pollution[255]. While knowledge and consumer intention do not always result in behaviour change[256], there is some evidence that these concerns about environmental change may translate into consumer choices; the Greendex study, a survey of 18 countries globally, highlighted Indian consumers as the “most easily influenced to change when they are informed about their personal impact on the environment”[257]. A similar study by Unilever, while only among five high and low-income countries, also recorded Indian consumers as having the highest preference for products with environmental or social purpose messaging[250]. This has been mirrored in a consumer survey across all world regions, with individuals in the Asia-Pacific region showing higher preference than Europeans or North Americans for companies and products with positive environmental impact[258]. However, few data exist specifically on these trends in relations to dietary choices, and there may be some barriers for sustainable eating specific to India: healthier and lower-footprint traditional grains such as millet may be seen as inferior products to wheat and rice, and considered to be a food product for lower-income individuals[39]. Additionally, meat intake may currently have positive socioeconomic connotations with being progressive, secular, and modern[104].

Nevertheless, given the high public awareness of environmental challenges, and consumer preference for environmentally-beneficial consumer choices, there may be an important opportunity to better inform Indian consumers about the links between dietary choices and environmental footprints. Central government can play a role, as several countries have now introduced dietary guidelines that include environmental considerations - most recently in Canada[259] and Brazil[260]. These are useful tools, as they influence a variety of entry points to dietary change, including school and other institutional feeding programmes, and inform the advice given by health professionals to patients. A systematic review has shown that food product labels do help inform dietary choice[261], though a widespread and agreed labelling system for environmental footprints does not yet exist (and should be developed)[262], while India is still currently drafting regulations on front-of-packaging health labels[263]. Other strategies may rely on advocacy and public messaging by civil society organisations[264], foundations[265], research institutions[266], and multilateral organisations[37] with strategic interests in this area. However, to date, no country has seen widespread adoption of healthy and low-footprint diets, and therefore successful case studies and lessons should be drawn as they occur over the coming years.

7.3 Limitations

The specific limitations of the studies are presented separately within each paper, though a number of over-arching points are presented below.

Dietary data

Given that very little work to date has focused on the area of diets, environmental sustainability, and cost in India, the results papers in the PhD largely focused on overall national-level trends, with some stratification among broad sub-population samples (by geographical regions comprising several states, rural/urban, quartiles of wealth, etc.). However, there is a huge cultural and socioeconomic diversity across India; the interactions between dietary shifts, environmental impacts, and cost at lower regional scales may differ from those seen at the broad scales assessed in this PhD, and may potentially yield different conclusions than those I presented. Future work should explore this diversity.

I did not have access to physical activity data that could be matched to the households and individuals in this analysis. This necessitated making assumptions on appropriate dietary energy intakes in the healthy scenarios: **Paper 3**, which optimised a hypothetical healthy diet, used a single caloric target of dietary energy assuming moderate physical activity, while **Paper 4**, categorising observed diets, used a healthy range between the dietary energy recommendations for low- to high-activity individuals. Analyses using more specific dietary energy targets for individuals may have produced somewhat different results. A recent study similar to

Paper 3, concluded that shifts to healthy diets in India would reduce GHG emissions[74] – a result opposite to mine. The scenario used in that paper assumed a dietary energy requirement that was an average between low- to moderate-physical activity; compared to my use of a moderate physical activity level, this would mean that undernourished individuals would have a smaller “gap” to reach their overall dietary targets and therefore result in a smaller increase in environmental impacts, and those who overconsume would have a slightly larger drop to a healthy dietary energy level, therefore resulting in greater environmental benefits. However, the two studies also contained a variety of other differences, including different underlying environmental footprint data for food items, an altered survey format of the NSS data, and other differences in the healthy scenario definition, among others. **Paper 4** had adjusted for dietary energy in the mixed effects models that tested for differences in cost, though the use of the broad dietary energy range for the healthy diet category may have overestimated the number of healthy individuals.

The dietary data used from the NSS, while the most recently available for India, are currently 7-8 years old. India is experiencing high rates of economic growth and urbanisation, both of which are important drivers of dietary change, and dietary patterns may have shifted somewhat since the data from 2011-2012. However, this degree of lag is common for much of the literature that also relies on dietary data from national surveys, which typically are not conducted annually.

There are a number of uncertainties in the NSS dataset itself. It records the quantity of food purchased by a household, and may not represent actual intake, as some food may be wasted or unused. Without a gold standard reference to validate the data against, it is not possible to assess whether it over- or underestimates intakes, though it has been reported that it may underestimate intake in a specific survey module relating to foods and meals eaten outside the home[267]. Additionally, the intake of nutrient-dense foods (including meats, eggs, fruit) may be somewhat uncertain, as seen in the relative comparison of dietary data sources in Paper 3. This could be partly due to these items being purchased irregularly and not well captured through recall. This may have impacted the categorisation of individuals into healthiness and footprint categories. However, the NSS is widely used among researchers and for generating official government statistics, and has to date produced plausible values on per capita dietary energy, macronutrient, and broad food group intakes. My estimation of individual-level intakes from the household-level data also potentially introduced bias, as food allocation within a household is likely not only based on age- and sex-specific dietary energy needs. However, recent work comparing household data to individual-level surveys has shown that using sex-specific dietary energy needs to make assumptions on individual intakes within a household is plausible[209,268].

Environmental data

Paper 4 identified individuals who consume a healthy and relatively lower footprint diet in India, though this scenario is unlikely to be an environmentally sustainable diet in absolute terms. For this, one would first need to define environmental boundaries or thresholds for each of the environmental indicators, for a given region and time range, and work backwards from these to define a dietary pattern that would meet these environmental (and health) parameters. Defining such a diet was not the objective of the papers, though such a diet could potentially look different than the ones identified. The planetary boundaries approach has set out thresholds for 9 earth system indicators (including climate change, stratospheric ozone depletion, freshwater use, and land-system change, among others), the breaching of which would substantially destabilise natural earth systems[23]. The thresholds are calculated at the global level, and national-level indicators for India do not yet exist. More on this point is discussed in the future work section below.

A strength of **Papers 1**, **3**, and **4** is their inclusion of three diet-related environmental indicators (GHG emissions, LU and WFs), as a large portion of the literature focuses on a single environmental outcome (GHG emissions). However, other important footprints were not incorporated, including biodiversity loss, and phosphorus and nitrogen use, which would be useful to define environmental sustainability in a more comprehensive way. A handful of studies included in **Paper 1** assessed these indicators, though there were too few to compare across diet types, and India-specific data for these indicators were not available during the PhD project.

The results papers did not generate uncertainty ranges for the environmental impacts calculated. An uncertainty range for an environmental footprint calculation should be a function of the uncertainty of the dietary data, the environmental data, and potentially the nutritional composition data. The environmental data used for all indicators were in the form of point estimates; some sources of data variability were available upon which it would be possible to generate a range of uncertainty (such as sub-national variability by Indian states for WFs), but this was not consistently available for all foods within an indicator, and not consistently across indicators (e.g.

no such additional data were available for the LU estimates). Additionally, the uncertainty range for the dietary data is very narrow due to the large sample size, and used on its own, would not represent the true uncertainty inherent in calculating diet-related environmental footprints.

Additionally, environmental footprint data were not available specifically for all 34 food groups and items used in the analysis in **Papers 3** and **4**, and proxy values from similar food groups had to be used in some cases for the missing items and groups. The major differences in environmental footprints occurred across the broader groupings of ruminant animals, non-ruminant animals, and crops (with some exceptions), and therefore the use of proxy values is unlikely to have strongly affected the overall results. However, more detailed environmental data would be useful for future analyses, to improve robustness and accuracy of the work.

7.4 Future work

The study of sustainable diets is still at an early stage of research relative to other global and environmental health challenges, and a variety of issues with data and methods require further development.

As mentioned in the limitations, the granularity of India-specific environmental footprint data could be improved, by widening the set of food items for which they are available, and generating them for individual Indian states or regions. It would also be useful to develop India-specific data on additional environmental indicators relevant to agriculture and diets, such as biodiversity loss, and phosphorus and nitrogen use. A newly funded programme may soon generate data for South Asia on the latter[269].

While the NSS data remain the most recent and comprehensive national-level data for estimating dietary intake, there may be challenges specifically in estimating foods eaten out of home. While it would be difficult to change the format of a such a large and long-running survey, small case studies using more detailed survey formats could be undertaken to compare or validate against the NSS out of home meals module. The Indian National Institute of Nutrition also conducts national (though not representative) dietary surveys using a 24 hour recall format; these data are not typically available to external users, and easier access to these would also be helpful for Indian analyses.

The trends investigated in the results papers of this PhD should also be assessed in more granularity across regions of India, as diets, patterns of development, and environmental context can differ markedly. For example, the role of fish, meat, rice and wheat in diets differs substantially across Indian states, as well as environmental challenges such as water scarcity and availability of cropland.

Further research is needed on methodological approaches to sustainable diet analyses. A variety of assumptions and modelling methods are used across the literature, including the specification of sustainable diet scenarios (e.g. the number and types of nutritional recommendations included within a national dietary guidelines scenario), the formulation of mathematical optimisation functions (the use of linear vs. nonlinear functions, and if/how preference for food groups is weighted), methods for generating uncertainty ranges for environmental impacts, and approaches to including uncertainty across several data inputs (i.e., from environmental, dietary, and nutritional composition data sources). These various methods and approaches should be compared, to understand how they may impact results. Similar efforts have been organised in other related areas, such as the Agricultural Model Intercomparison and Improvement Project (AgMIP)[270], and among the research community assessing the health co-benefits of mitigating greenhouse gas emissions.

While work on sustainable diets is limited (particularly in LMICs such as India), and cross-sectional comparisons between different dietary patterns are useful for highlighting the overall context, future work should increasingly take a “pathways” approach, and incorporate additional complexities of demographics, trade, affordability, and agricultural production feedback systems, where possible. Such analyses should increasingly ask the question of how to meet dietary needs within environmental parameters, and which agricultural and dietary trajectories and strategies would support this. Given the urgency and magnitude of action needed to improve food systems, such a framing would potentially be more policy-relevant and useful for decision-makers. The recent EAT-Lancet report and related analyses are examples of such an approach[271,272]. An increased focus of future sustainable diet analyses should be LMICs, where little work to date has been done, and the nutritional and environmental challenges are arguably more complex than in HICs, though evidence on food system solutions is urgently needed for all countries.

To facilitate the recommendation above, national-level thresholds or targets for environmental indicators should be devised for countries, including India. Such targets would provide the environmental limits within which agriculture and diets should aim to operate. A variety of health targets exist such as the WHO's Global Targets 2025 for maternal and child health[273] and Global Action Plan for NCDs[274], as well as the United Nations' Sustainable Development Goals (SDGs), though little exists for the environment. The Paris Agreement, signed by most countries, including India, sets out a target of limiting global average temperatures to a 2^{o}C increase since pre-industrial times. Such high-level and high-profile targets do not yet exist for other environmental indicators for countries. The planetary boundaries approach has been useful in highlighting the absolute thresholds for a number of environmental indicators globally, and work is beginning to consider frameworks for translating these to national targets[275], though not specifically for the agricultural sector. Meanwhile, the recent EAT-Lancet report on sustainable diets has used the planetary boundaries framework to propose global targets specifically for food systems, for six boundaries (GHG emissions, nitrogen and phosphorus cycling, freshwater and cropland use, and biodiversity loss)[271]. However, national-level targets for these food system-specific thresholds do not yet exist.

Lastly, given evidence of lower costs for improved diets for some portions of the population (both in my **Paper 4**, and others in the literature), additional research should examine behavioural and cultural barriers to dietary change. To date, few studies have investigated consumer demand for sustainable diets[38], and such insights will be critical to understanding how to implement the strategies and recommendations generated by sustainable diet studies.

7.5 Conclusions

Shifting current average diets to a variety of alternative dietary patterns has been estimated to offer both health and environmental benefits in HICs. In India, widespread adoption of national dietary guidelines would result in small increases in diet-related GHG emissions, WFs and LU. However, these footprints would be far lower, and the health impacts more positive, than an alternative trajectory to affluent diets. Additionally, healthy and lower-footprint diets were found to be unaffordable for many Indians, with exceptions for some portions of the population. Therefore, to achieve the critical public health goal of adoption of healthy diets while minimising current agricultural environmental pressures, three broad strategies are recommended: increasing the efficiency of agricultural production, alongside efforts to improve affordability of healthy dietary change, and the promotion of healthy and lower-footprint diets.

References

The references list below is for literature cited in the narrative sections of the thesis (Introduction, Background on Methods, and Discussion). References cited within chapters that comprise a research paper (Chapters 3-6) are found at the end of each individual paper.

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Appendix 1: Ethical approval for Paper 2

London School of Hygiene & Tropical Medicine
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LONDON SCHOOL of HYGIENE &TROPICAL MEDICINE

Observational / Interventions Research Ethics Committee

Mr Lukasz Aleksandrowicz
LSHTM

10 May 2016

Dear Lukasz

Study Title: Food consumption in India: comparison of intake estimates using national and regional dietary data sources

LSHTM Ethics Ref: 11439

Thank you for your application for the above research project which has now been considered by the Observational Committee via Chair's Action.

Confirmation of ethical opinion

On behalf of the Committee, I am pleased to confirm a favourable ethical opinion for the above research on the basis described in the application form, protocol and supporting documentation, subject to the conditions specified below.

Conditions of the favourable opinion

Approval is dependent on local ethical approval having been received, where relevant.

Approved documents

The final list of documents reviewed and approved is as follows:

Document Type	File Name	Date	Version
Local Approval	IMS HMSC	14/04/2016	IMS
Local Approval	Kinra_6471_approval_29072013_1	14/04/2016	APCAPS
Protocol / Proposal	Protocol Diet Comparison	15/04/2016	1
Investigator CV	CV_Aleksandrowicz	15/04/2016	1
Investigator CV	AHaines brief CV	15/04/2016	1
Investigator CV	CV Rosie Green for GFS project	21/04/2016	1

After ethical review

The Chief Investigator (CI) or delegate is responsible for informing the ethics committee of any subsequent changes to the application. These must be submitted to the committee for review using an Amendment form. Amendments must not be initiated before receipt of written favourable opinion from the committee.

The CI or delegate is also required to notify the ethics committee of any protocol violations and/or Suspected Unexpected Serious Adverse Reactions (SUSARs) which occur during the project by submitting a Serious Adverse Event form.

At the end of the study, the CI or delegate must notify the committee using the End of Study form.

All aforementioned forms are available on the ethics online applications website and can only be submitted to the committee via the website at: http://leo.lshtm.ac.uk.

Further information is available at: www.lshtm.ac.uk/ethics.

Yours sincerely,

[redacted]

Professor John DH Porter
Chair

ethics@lshtm.ac.uk
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Appendix 2: Ethical approval for Papers 3 & 4

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LONDON SCHOOL *of* HYGIENE &TROPICAL MEDICINE

Observational / Interventions Research Ethics Committee

Mr Lukasz Aleksandrowicz
LSHTM

29 June 2018

Dear Lukasz,

Study Title: Impact of dietary shift in India on greenhouse gas emissions, land use, water use, and food expenditure: a nationally-representative modelling study

LSHTM Ethics Ref: 15926

Thank you for your application for the above research project which has now been considered by the Observational Committee via Chair's Action.

Confirmation of ethical opinion

On behalf of the Committee, I am pleased to confirm a favourable ethical opinion for the above research on the basis described in the application form, protocol and supporting documentation, subject to the conditions specified below.

Conditions of the favourable opinion

Approval is dependent on local ethical approval having been received, where relevant.

Approved documents

The final list of documents reviewed and approved is as follows:

Document Type	File Name	Date	Version
Investigator CV	AHaines brief CURRICULUM VITAE (1)	22/06/2018	Andy
Investigator CV	CV Rosie Green for GFS project	22/06/2018	Rosie
Investigator CV	CV_june2018	22/06/2018	Aleksandrowicz
Protocol / Proposal	Protocol India dietary enviro footprints	25/06/2018	1.2

After ethical review

The Chief Investigator (CI) or delegate is responsible for informing the ethics committee of any subsequent changes to the application. These must be submitted to the committee for review using an Amendment form. Amendments must not be initiated before receipt of written favourable opinion from the committee.

The CI or delegate is also required to notify the ethics committee of any protocol violations and/or Suspected Unexpected Serious Adverse Reactions (SUSARs) which occur during the project by submitting a Serious Adverse Event form.

An annual report should be submitted to the committee using an Annual Report form on the anniversary of the approval of the study during the lifetime of the study.

At the end of the study, the CI or delegate must notify the committee using the End of Study form.

All aforementioned forms are available on the ethics online applications website and can only be submitted to the committee via the website at: http://leo.lshtm.ac.uk.

Further information is available at: www.lshtm.ac.uk/ethics.

Yours sincerely,

[redacted]

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Chair

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